ACTA Mineralogica Petrographica

Acta Mineralogica-Petrographica, Field Guide Series, Vol. 27, pp. 1–36.



# Rock-forming and accessory minerals as tracers of magmatic and metamorphic evolution of the Western Carpathians, Slovakia

Edited by Pavel Uher[1*] and Igor Broska[2]

[1] Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina G, 842 15 Bratislava, Slovakia; puher@fns.uniba.sk (*corresponding author)

[2] Geological Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 06 Bratislava, Slovakia; igor.broska@savba.sk

Written by Pavel Uher[1*], Igor Broska[2a] and Marián Janák[2b]

[1] Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina G, 842 15 Bratislava, Slovakia; puher@fns.uniba.sk (*corresponding author)

[2] Geological Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 06 Bratislava, Slovakia; [a]igor.broska@savba.sk; [b]geolmjan@savba.sk

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# 1. Introduction

The field trip represents an introduction to the complex and variegated geological history of a relatively small territory of Slovakia in Central Europe. During the field trip, a cross-section showing the Hercynian (Variscan) crystalline basement and overlaying sedimentary cover and magmatic rocks of the principal Alpine tectonic units is presented. The stops represent a diversified selection of almost twenty interesting mineralogical-petrological localities from Bratislava, the capital of Slovakia, through the Tatra Mountains, the highest mountains in the Carpathians in northern Slovakia, to the volcanic area of the Cerová Highland along the southern border of Slovakia with Hungary. From the geological point of view, the program of the field trip presents a sequence from the oldest Paleozoic metamorphic and magmatic rocks to the youngest Tertiary/Pleistocene alkaline volcanic rocks, from ultrabasic rocks to granites and pegmatites. Magmatic, metamorphic, hydrothermal and supergene mineralizations will be shown, as a results of various endogenous to exogenous processes. Some of the field-trip localities have been famous since the 18–19th century as classic Central European mineral occurrences (libethenite, euchroite and mrázekite from Ľubietová; devilline, celestine and aragonite from Špania Dolina), two stops represent unique ice and aragonite caves (Dobšiná, Ochtiná). However, a majority of the visited localities show the newest results of recent mineralogical and petrological studies of numerous Slovak and international authors.

The route is relatively long (about 800 km) and includes 3-4 localities every day, but each participant will be introduced also to important natural and historical monuments of Slovakia, including high mountains, national parks, UNESCO World Heritage sites, picturesque castle ruins, medieval cities and typical villages, as well as tasting of original Slovak wines. The field trip is starting in Bratislava at the Natural History Museum with mineral collection and finish in the Eötvös Loránd University in Budapest where the IMA Congress will be held.

Welcome to Slovakia and the Western Carpathians, and enjoy their beauty, geological and historical monuments, country and people.

## 1.1 Location and tectonic setting of the Western Carpathians

The tectonic structure of the Western Carpathians is the result of Hercynian and Alpine orogenesis and from the north, it is underlain by the submerged European platform, which is mainly Cadomian in age. The Western Carpathians create the northernmost, generally E–W trending orocline of the European Alpides, and thus they are linked to the Eastern Alps in the west and to the Eastern Carpathians in the east (Fig. I). A large part of the Central and most of the Internal Western Carpathians are covered by remnants of Paleogene sedimentary basins and thick Neogene sedimentary and volcanic rock complexes, which are related to the hinterland of the Pannonian Basin. The present structural pattern of the Western Carpathians originated from the Late Jurassic–Tertiary subduction–collision orogenic processes in a mobile belt between

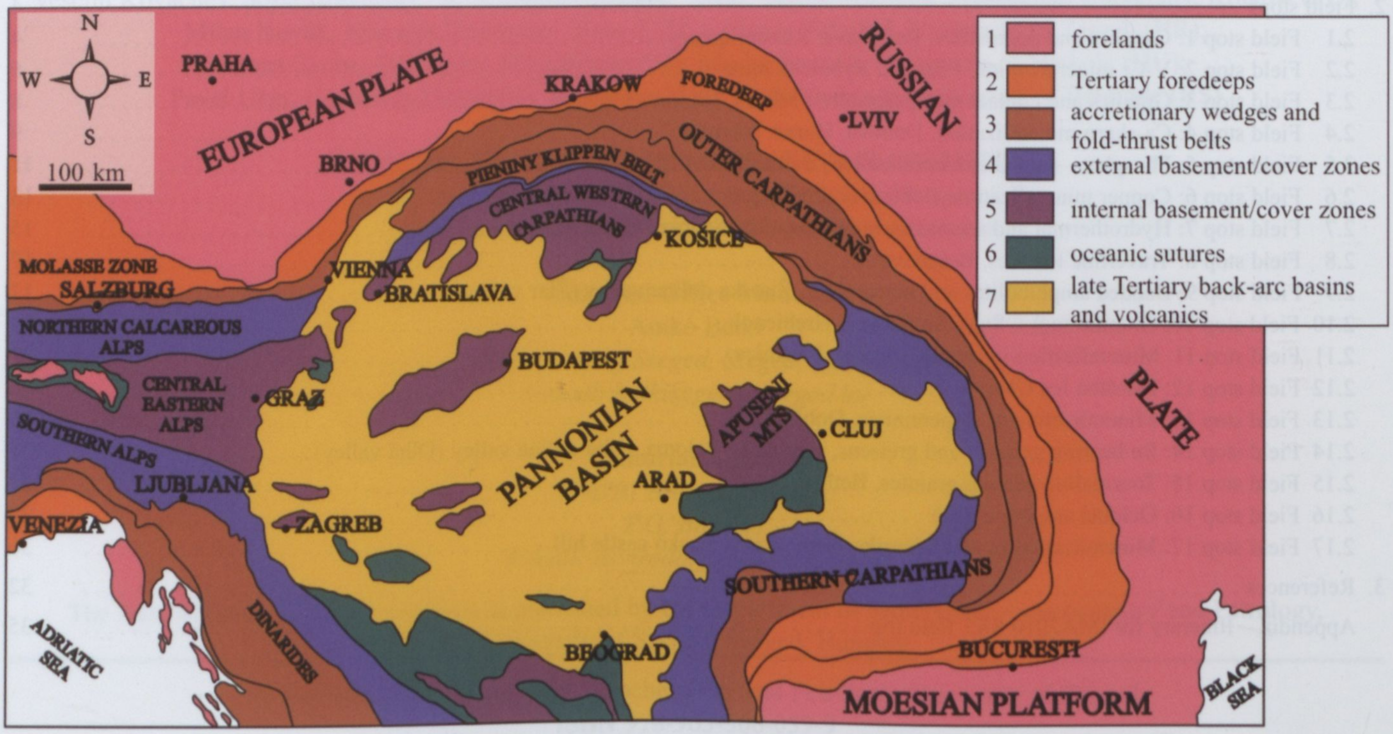


**Fig. I.** Principal tectonic units of the Eastern Alps–Carpathians–Pannonian area (Plašienka *et al.*, 1997, adapted).

the stable North European Plate and Africa-related, drifting Apulian continental fragments. One of the most characteristic features of the Western Carpathian evolution is a marked northward migration of pre-orogenic and orogenic processes (see *e.g.*, Maheľ, 1986; Plašienka *et al.*, 1997). Recently, a concept of triple division into the External, Central and Internal Western Carpathians (Plašienka *et al.*, 1997) is accepted.

## 1.2 Pre-Alpine crystalline basement of the Western Carpathians

The oldest tectonic units of Slovakia are built up by fragments of the Hercynian (Variscan) orogeny, which are recently incorporated into the Alpine nappe system (Fig. II). The pre-Alpine crystalline basement of Slovakia mainly consist of Upper Proterozoic (?) to Lower Paleozoic metapelites, metapsammites, metabasaltic and metagabbroic rocks, orthogneisses, rarely metacarbonates, metamorphosed mainly in greenschist to amphibolite facies, rarely in granulite or eclogite facies. The basement units are intruded by Hercynian (Devonian to Pennsylvanian) S- and I-type orogen-related granites, granodiorites and tonalites, rarely dioritic rocks exposed in so-called core mountains (Fig. III). Granitic pegmatites, locally with beryl and Nb-Ta minerals are connected with the Hercynian granitic rocks (Uher *et al.*, 1994, 1998a,b). Hydrothermal gold, scheelite and sulphide mineralization is connected to the Hercynian orogeny. The crystalline basement was developed between Laurasia and Gondwana or fragment of Gondwana during the Hercynian orogeny, mainly in the Devonian/Mississippian periods. The Paleozoic basement rocks are arranged in a Hercynian crustal nappe system (see *e.g.*, Bezák, 1994; Putiš *et al.*, 2009).

The post-Hercynian Permian stage is characterized by development of extensional sedimentary basins filled up by clastic sediments and extensive volcanic and plutonic activity with basalt and andesite, A-type rhyolite, dacite and granite (see *e.g.*, Vozárová & Vozár, 1988; Uher & Broska, 1996). Intrusions of specialized S-type granites with greisen and albitite cupolas rich in Li, B, Sn, W, Nb, Ta were developed in the Gemeric Unit (see *e.g.* Grecula, 1995; Uher & Broska, 1996; Malachovský *et al.*, 2000).

## 1.3 Alpine evolution of the Western Carpathians

The Alpine orogenesis lasted in Mesosozoic and Cenozoic eras and is divided into Paleo-Meso- and Neo-Alpine phases according to the closing of three different oceanic domains between the North European Platform and Africa or Apulia, a fragment of Africa continent. The Paleo-Alpine phase is related to the closure of the Meliata oceanic basin in the Jurassic period, the Meso-Alpine phase to the closure of the South Penninic or a hypothetical Vahic ocean following compressional events at the end of the Cretaceous period. At that time, the principal Alpine tectonic units have been stacked: Tatric, Veporic and Gemeric (Maheľ 1986; Plašienka *et al.*, 1997). Some important hydrothermal siderite–sulphide and talc deposits were developed during the Paleo- to Meso-Alpine stage, mainly in the Gemeric Unit.

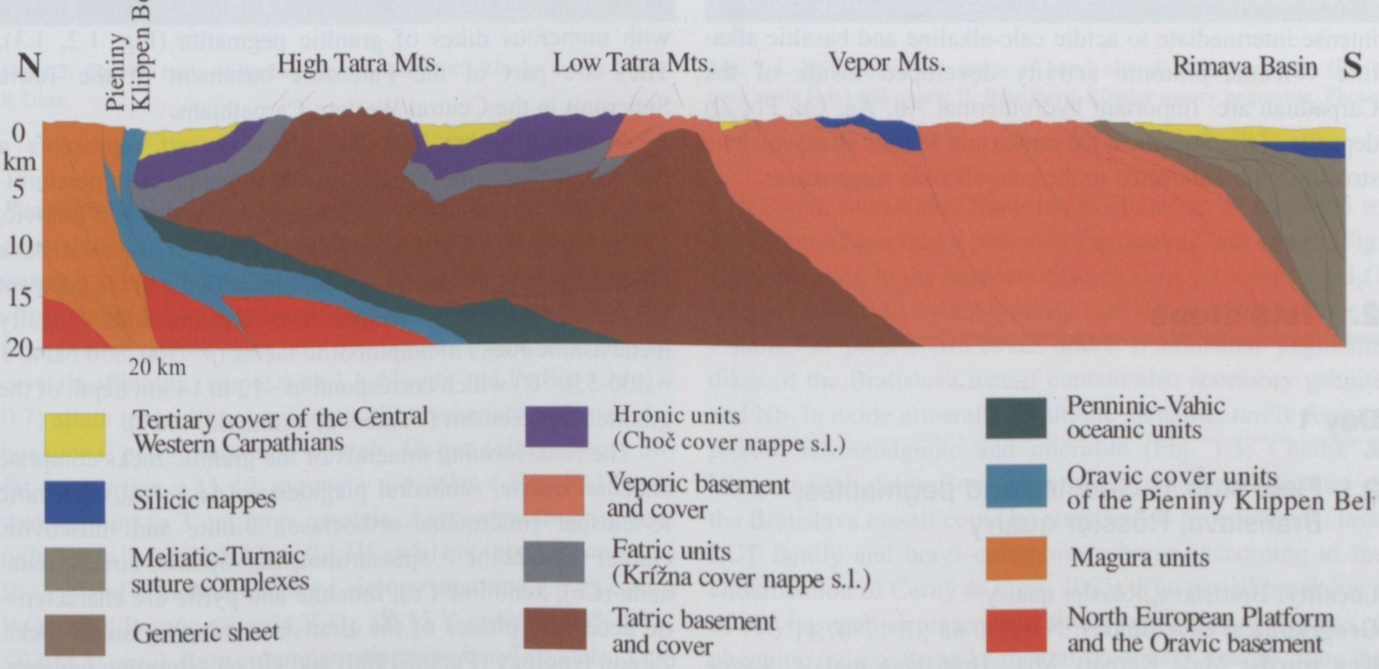


**Fig. II.** Idealized geological cross-section of the Western Carpathians (Plašienka *et al.*, 1997, adapted).

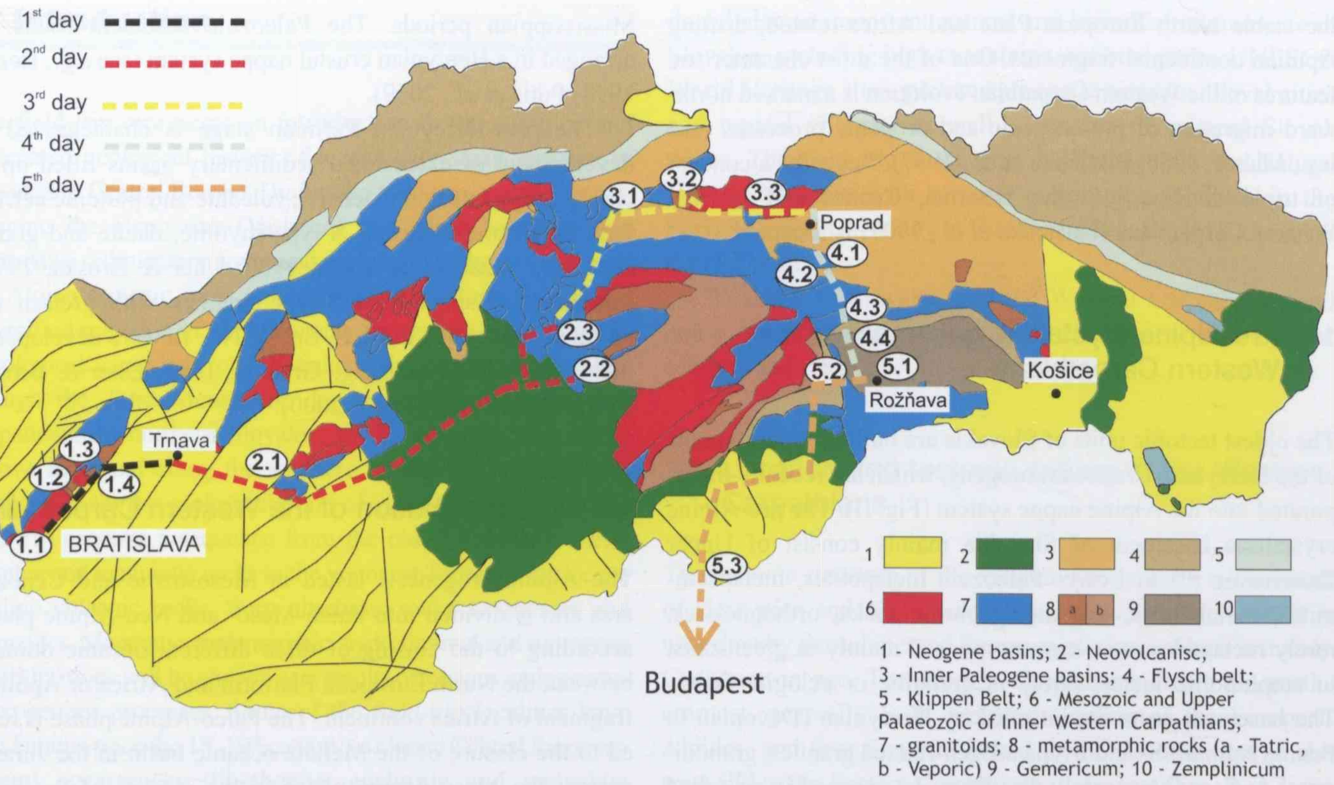


**Fig. III.** Simplified geological map of Slovakia (according to Biely *et al.*, 1996) with excursion route.

The Neo-Alpine phase means the closure of the North-Penninic ocean at the end of Paleogene and begining of Neogene. The Early Miocene oblique "soft" collision of the Western Carpathian orogen with the North European Platform led to a change of movement direction of the overriding plate and was accompanied by the counterclockwise rotation, transpression–transtension and uplift of rigid basement blocks, creating the present "core mountains" inside the Carpathian arc (see *e.g.*, Kováč *et al.*, 1997). During Neogene to Pleistocene, intense intermediate to acidic calc-alkaline and basaltic alkaline volcanic–plutonic activity developed inside of the Carpathian arc. Important hydrothermal Au, Ag, Cu, Pb, Zn deposits of the Štiavnica, Kremnica and Javorie stratovolcanic structures are connected to the calc-alkaline magmatism.

## 2. Field stops

### Day 1

### 2.1 Field stop 1: Granites and pegmatites, Bratislava, Rössler quarry

**Locality:** Bratislava, Rössler quarry
**Geographical coordinates:** N 48°10.88′; E 17°07.11′
**Key words:** Malé Karpaty Mts., Bratislava massif, S-type granite, granitic pegmatite, rock-forming and accessory minerals, biotite, muscovite, garnet, zircon, monazite, beryl, phenakite, Nb-Ta oxide minerals

**Locality description:**
***Position:*** The abandoned Rössler quarry (Rösslerov lom) is situated on the eastern slope of the Kamzík hill, Malé Karpaty (Small Carpathians) Mountains, in the NE part of Bratislava (Fig. 1.1). The exposed rocks are biotite, locally muscovite-biotite granodiorite to monzogranite of the Bratislava massif with numerous dikes of granitic pegmatite (Fig. 1.2, 1.3). They are part of the Paleozoic basement of the Tatric Superunit in the Central Western Carpathians.

***Granitic rocks:*** The Bratislava massif represents a Hercynian (Variscan) orogen-related intrusion with peraluminous, calc-alkaline and S-type character (Cambel & Vilinovič, 1987; Petrík *et al.*, 2001). The intrusion of the Bratislava granitic massif generated metamorphic aureole in the adjacent Lower Paleozoic metapelitic-metapsammitic, locally metabasaltic rocks in amphibolite facies ($p$ ~300–350 MPa, $T$ = 500-550 °C) which correspond to ~12 to 14 km depth of the granite emplacement (Cambel & Vilinovič, 1987).

The rock-forming minerals of the granitic rocks comprise anhedral quartz, subhedral plagioclase ($An_{24}$–$An_{06}$), perthitic K-feldspar (microcline–orthoclase), biotite and muscovite. Garnet (almandine > spessartine), fluorapatite, zircon, monazite-(Ce), xenotime-(Y), ilmenite and pyrite are characteristic accessory phases of the Bratislava massif granitic rocks. Zircon typology (Pupin, 1980) and zircon saturation temperature indicate ~750 to 700 °C main temperature interval.

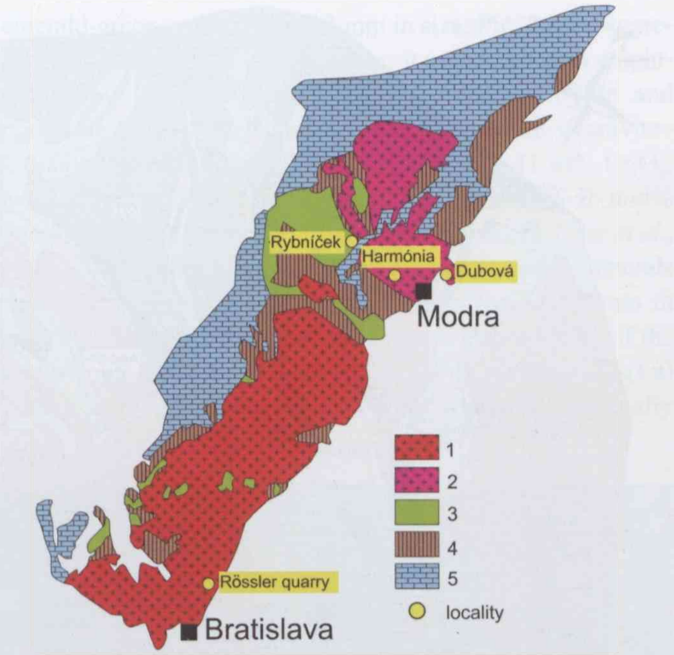


**Fig. 1.1.** Geological sketch of Malé Karpaty Mts. and position of localities planned during first day of excursion.

**Fig. 1.2.** Granitic rocks of the Bratislava massif in the Rössler quarry. Photo: P. Uher.

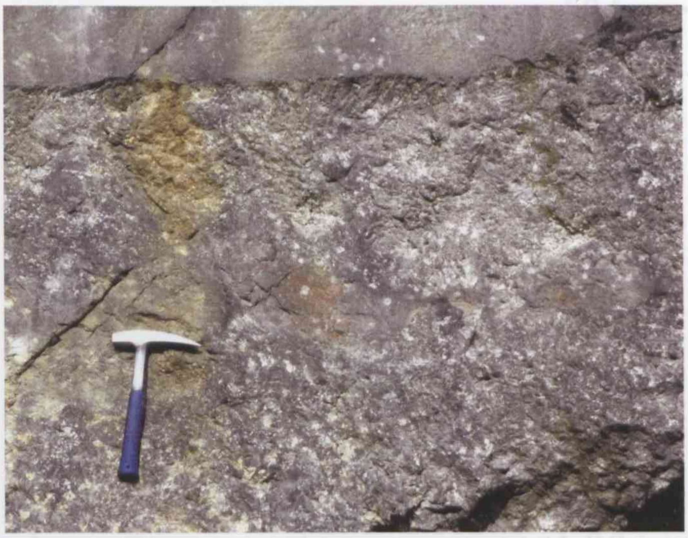

**Fig. 1.3.** Pegmatite dike cutting granodiorite in the Rössler quarry. Photo: P. Uher.

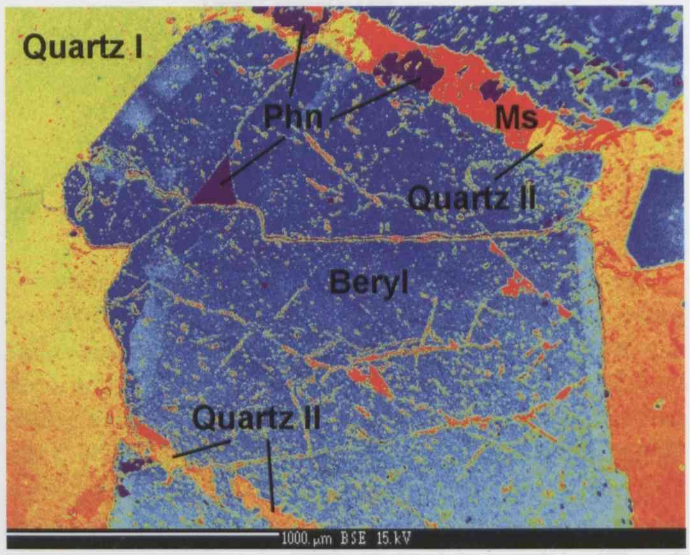


**Fig. 1.4.** BSE photomicrograph of beryl alteration to phenakite (Phn), muscovite (Ms) and quartz II. Bratislava, Rössler quarry pegmatite. Photo: P. Konečný.

***Pegmatites:*** Dikes of granite pegmatite (up to 3 m thick) show general zoning with dominant coarse-grained alkali feldspar + quartz + biotite + muscovite zone, blocky K-feldspar (microcline) zone and quartz core. Locally graphic pegmatite and fine-grained aplitic zone are developed. Black, thin tabular crystals of biotite (annite with 1.6 Al *apfu* and Fe/(Fe + Mg) = 0.7) attain up to 40 cm in length; they associate with pseudohexagonal platy muscovite crystals. Garnet (almandine ≈ 50-60, spessartine ≈ 35-40, pyrope + grossular ≤ 5 mol%) forms dark red, up to 3 cm large crystals. Accessory zircon shows only 1.2 to 3.1 wt% $HfO_2$ (=0.1 Hf *apfu*) but it locally contains P-, Y-, and U-rich domains of zircon–xenotime *s.s.* (≤7 wt% $P_2O_5$, =0.2 P *apfu*; ≤8 wt% $Y_2O_3$, ≤0.15 Y *apfu*; ≤2 wt% $UO_2$, ≤0.015 U *apfu*). Rare columnar pale green beryl crystals (2 cm long) associate with coarse-grained quartz, muscovite and K-feldspar. Subsolidus fluid-driven alteration of beryl led to formation of secondary phenakite, muscovite and quartz (Fig. 1.4) according to the reaction: $6Be_3Al_2(Si_6O_{18}) + 4K^+ + 4H_2O + O_2 = 9Be_2(SiO_4) + 4KAl_2(AlSi_3O_{10})(OH)_2 + 15SiO_2$ (Uher & Chudík, *in prep.*). Moreover, more fractionated pegmatite dikes of the Bratislava massif contain also accessory gahnite and Nb-Ta oxide minerals: columbite–tantalite, rarely ferrotapiolite, ferrowodginite and microlite (Fig. 1.5; Chudík & Uher, unpubl. data). Consequently, the granitic pegmatites of the Bratislava massif could be classified as rare-element class, LCT family and beryl–columbite subtype (according to the classification of Černý & Ercit, 2005). The partial breakdown of beryl as well as presence of finely crystalline aggregates of phengitic muscovite and anhedral secondary titanite along the margin of large biotite crystals indicates a slight Alpine

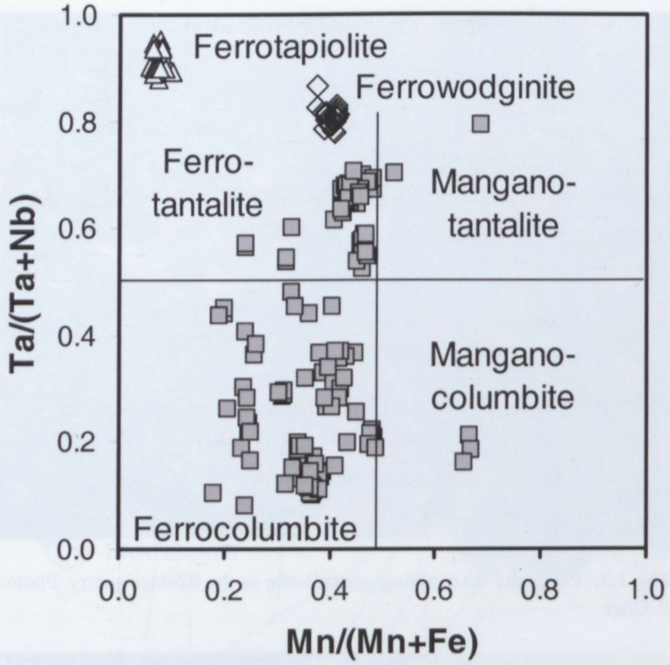


**Fig. 1.5.** Quadrilateral diagram of the Nb-Ta oxide minerals from the Bratislava massif pegmatites (Chudík & Uher, unpubl. data).

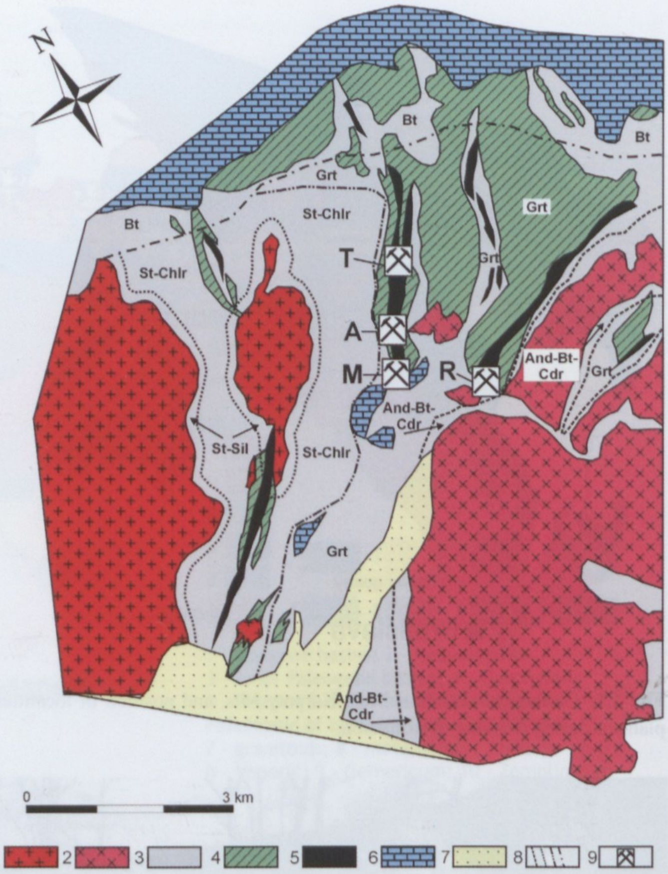


**Fig. 2.1.** Schematic geological map of the Pezinok–Pernek area in the Malé Karpaty Mts. (Cambel & Vilinovič 1987, adapted). 1 – Bratislava granitic massif; 2 – Modra granitic massif; 3 – metapelites; 4 – metabasic rocks; 5 – pyrite–pyrrhotite-enriched metabasic rocks (1 to 5 Paleozoic); 6 – Mesozoic sedimentary rocks; 7 – Cenozoic sedimentary rocks; 8 – metamorphic isogrades; 9 – pyrite–pyrrhotite deposits with V-Cr mineralization: Rybníček (R), Trojárová (T), Augustín (A) and Michal (M).

tectono-metamorphic and hydrothermal overprint of the Bratislava massif granite and pegmatite.

*Age:* U-Pb zircon SHRIMP and monazite electron-microprobe dating indicate a Mississippian (Early Carboniferous) age of crystallization and emplacement of the Bratislava massif (355 ± 5 Ma by SHRIMP - Kohút *et al.*, 2009; 353 ± 2 Ma by CHIME – Uher *et al.*, unpubl. data). The monazite CHIME dating of the Rössler quarry granodiorite gave 359 ± 8 Ma (MSWD = 0.65, N = 34), and the Rössler quarry pegmatite dike showed the CHIME age of 352 ± 5 Ma (MSWD = 1.08, N = 30) – Uher *et al.* (unpubl. data).

## 2.2 Field stop 2: V-Cr mineralization, Pezinok, Rybníček mine

**Locality:** Pezinok, Rybníček mine

**Geographical coordinates:** N 48°21.57′; E 17°13.92′

**Key words:** Malé Karpaty Mts., Pernek metaophiolite complex, amphibole–pyrrhotite–pyrite metabasic rocks, black schists, V-Cr mineralization, goldmanite, dissakisite, mukhinite, V-rich muscovite, diopside, metamorphic evolution

**Locality description:**

***Position:*** The Rybníček mine is situated in the pyrrhotite–pyrite-bearing productive horizon within the Pernek meta-ophiolite complex (Pernek Group), NW of Pezinok town, in the Malé Karpaty Mountains (Fig. 2.1). The Pernek Group belongs to the Paleozoic basement of the Tatric Superunit, Central Western Carpathians.

***Adjacent rocks:*** The host rocks represent relicts of a metamorphosed Devonian ophiolite suite; metabasalts with oceanic pelitic metasediments rich in organic carbon and volcanic admixture (black schists). Stratiform, pyrrhotite–pyrite horizons are widespread. The Pernek meta-ophiolite complex has been overprinted by Hercynian regional metamorphism and younger contact thermal event caused by an intrusion of the Modra granitic massif dated by SHRIMP on zircon at 347 ± 4 Ma (Kohút *et al.*, 2009) or by electron-microprobe method on uraninite at 345 ± 2 Ma (Uher & Bačík, unpubl. data). Amphibole–pyrrhotite–pyrite metabasic rocks represent a special lithological type showing high concentrations of S, $C_{org}$, V, Cr, Ni, Cu and other metallic elements (Khun *et al.*, 1983) as well as unique silicate mineralization with V- and Cr-rich silicate phases.

***Metamorphic mineralization:*** In the Rybníček mine, the amphibole–pyrrhotite–pyrite metabasic rocks contain 1150 g/t V and 760 g/t Cr (Uher *et al.*, 2008), which resulted in appearance of V and Cr-bearing members of garnet, epidote and mica groups. The V-Cr garnet forms euhedral to subhedral emerald-green crystals (up to 3 mm in size; Fig. 2.2) or aggregates with anomalous birefringence; it associates with amphibole, albite, diopside, epidote-group minerals, pyrite and pyrrhotite (Fig. 2.3). Garnet shows goldmanite–uvarovite–grossular composition with 5–22 wt% $V_2O_3$, 5–11 wt% $Cr_2O_3$, and 1–13 wt% $Al_2O_3$ (16–72 mol% goldmanite, 19–36 mol% uvarovite, and 4–59 mol% grossular end-members; Uher *et al.*, 1994, 2008, unpubl. data; Fig. 2.4). Epidote-group minerals form euhedral to anhedral porphyroblasts (up to 0.5 mm in size, Fig. 2.5) or fine-grained aggregates. Central parts of the porphyroblasts consists of V- and Cr-rich dissakisite-(La) with V = 0.33 *apfu*, Cr = 0.44 *apfu*, which is continually verging to REE-rich mukhinite with REE = 0.46 *apfu* and Cr 0.13–0.43 *apfu*; Pezinok, Rybníček mine is a second world locality of dissakisite-(La) (Bačík & Uher, unpubl. data). Two generations of clinozoisite are present at the rim of dissakisite-mukhinite crystals. Clinozoisite I is V- and Cr-rich (V = 0.40 *apfu*, Cr = 0.42 *apfu*) and it forms overgrowths on dissakisite–mukhinite cores. The second generation of V-, Cr- and REE-poor clinozoisite II is replacing mukhinite and clinozoisite I at the rim and in the fissures of crystals. Muscovite forms subhedral, lamellar, greenish crystals, up to 1 mm in size, in association with amphibole, quartz, and pyrite/pyrrhotite or tiny, up to 0.1 mm, subhedral to anhedral, colourless crystals

**Fig. 2.2.** Emerald green crystals of goldmanite, 1-2 mm in size. Pezinok, Rybníček mine. Photo: A. Russ.

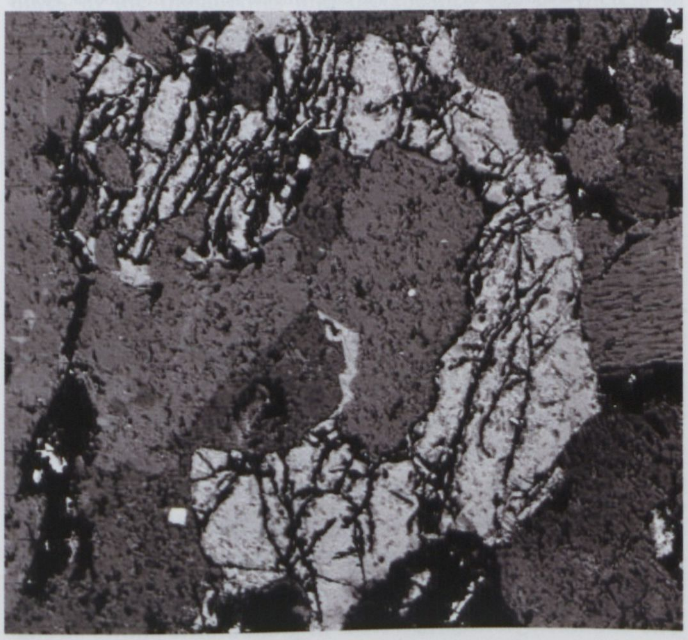

**Fig. 2.3.** BSE photomicrograph of skeletal crystal of goldmanite, (~1 mm in size) in association with amphibole (pale grey) and albite (dark grey). Pezinok, Rybníček mine. Photo: D. Ozdín.

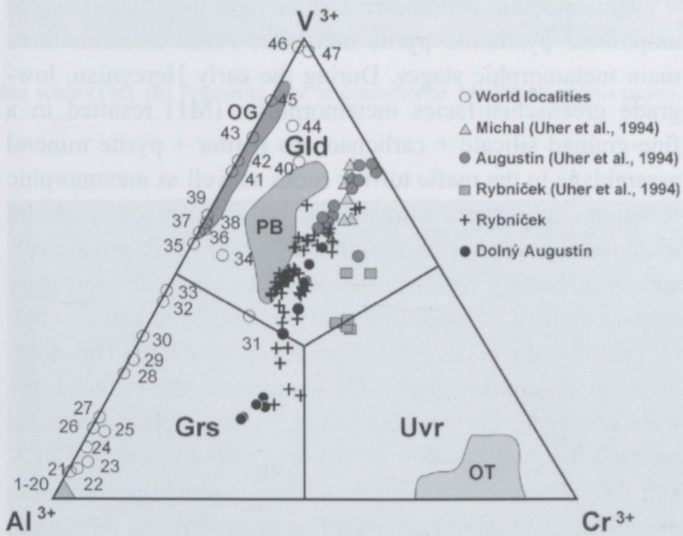


**Fig. 2.4.** Composition of goldmanite (Gld) – grossular–dissakisite-(La) (Grs) – uvarovite (Uvr) garnet from Pezinok area (Pernek Group) in comparison to the known world occurrences of V-Cr garnet (OG – Ogcheon belt, S. Korea; PB – Poblet area, Spain; OT – Outokumpu, Finland; numbers – other localities; Uher *et al.*, 1994b)

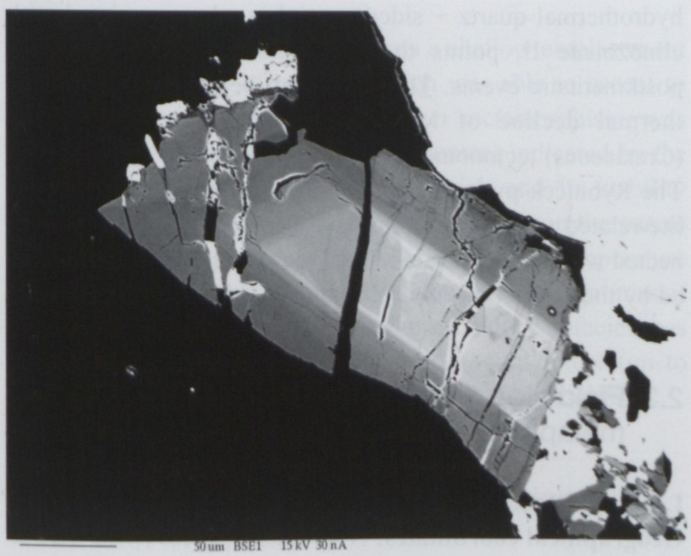

**Fig. 2.5.** BSE photomicrograph of zoned mukhinite crystal in pyrite (white). Rybníček mine. Photo: P. Konečný

in the groundmass. Two muscovite generations are recognized: V,(Cr)-rich muscovite I with 2.5–8 wt% $V_2O_3$ and 0–7 wt% $Cr_2O_3$ (0.12–0.45 and up to 0.39 *apfu* V and Cr, respectively) and V,Cr-free muscovite II with =0.4 wt% $V_2O_3$ and $Cr_2O_3$. Amphibole is the most common porphyroblast, forming aggregates and more rarely, individual euhedral to subhedral crystals. The amphiboles are classified as magnesiohornblende, actinolite, tremolite, rarely edenite with high Mg/(Mg + Fe) ratio (0.84–0.99). Locally, elevated V and Cr contents of up to 2.6 wt% $V_2O_3$ (0.3 V *apfu*) and up to 0.9 wt% $Cr_2O_3$ (0.1 Cr *apfu*) occur in amphiboles (Uher *et al.*, 2008). Diopside shows a nearly pure diopside composition, with up to 2.5 wt% $Al_2O_3$, 1.7 wt% $V_2O_3$, 0.4 wt% $Cr_2O_3$, and 2.5 wt% FeO.

***Metamorphic evolution:*** The mineral association in the amphibole–pyrrhotite–pyrite metabasic rocks indicates three main metamorphic stages. During the early Hercynian, low-grade greenschist-facies metamorphism (M1) resulted in a fine-grained silicate + carbonaceous matter + pyrite mineral assemblage in the mafic tuffitic rocks as well as metamorphic foliation. Subsequent intrusion of the late-orogenic, Modra tonalites to granodiorites into the folded Lower Paleozoic volcano-sedimentary rocks caused late Hercynian, low-pressure contact thermal metamorphism at $p$ = 200 MPa and $T$ = 580 °C (Korikovsky *et al.*, 1985; Cambel *et al.*, 1989). This dominant metamorphic event (M2) overprinted the regional M1 metamorphism. The peak contact M2 metamorphic conditions resulted in crystallization of silicate minerals enriched in V and Cr (garnet, dissakisite–mukhinite, amphibole, diopside, muscovite I), pyrite recrystallization and pyrrhotite formation. The youngest metamorphic event (M3) clearly shows a retrograde character in comparison to the M2 stage. During M3, a metamorphic association formed under prehnite–pumpellyite-facies conditions, which consists of phases low in V and Cr, *i.e.*, pumpellyite-(Mg), muscovite II, clinozoisite II and prehnite, and possibly albite II and clinochlore II. Thin hydrothermal quartz + siderite veinlets, also associated with clinozoisite II, points to remobilization during the latest postkinematic events. This event can be connected with the thermal decline of M2 or more probably with Alpine (Cretaceous) tectonometamorphic processes.

The Rybníček pyrite–pyrrhotite deposit belongs to an ophiolite-related volcanogenic massive suphide deposit type connected with a black-shale related metal enrichment overprinted by the contact metamorphism.

## 2.3 **Field stop 3:** Granites and contact metapsammites, Modra, Harmónia quarry

**Locality:** Modra, Harmónia quarry
**Geographical coordinates:** N 48°21.76′; E 17°18.54′
**Key words:** Malé Karpaty Mts., Modra granite massif, I-type granite, contact metamorphism, metapelites to metapsammites, cordierite schists, phyllites

**Locality description:**
***Position:*** The abandoned quarry is situated in the valley above water reservoir in Harmónia (part of Modra town). The exposed rocks are biotite granodiorite of the Modra massif with crystalline schist of metapelite superimposed by contact metamorphism (Figs. 3.1–3.2). They belong to the Paleozoic basement of the Tatric Superunit, Central Western Carpathians.

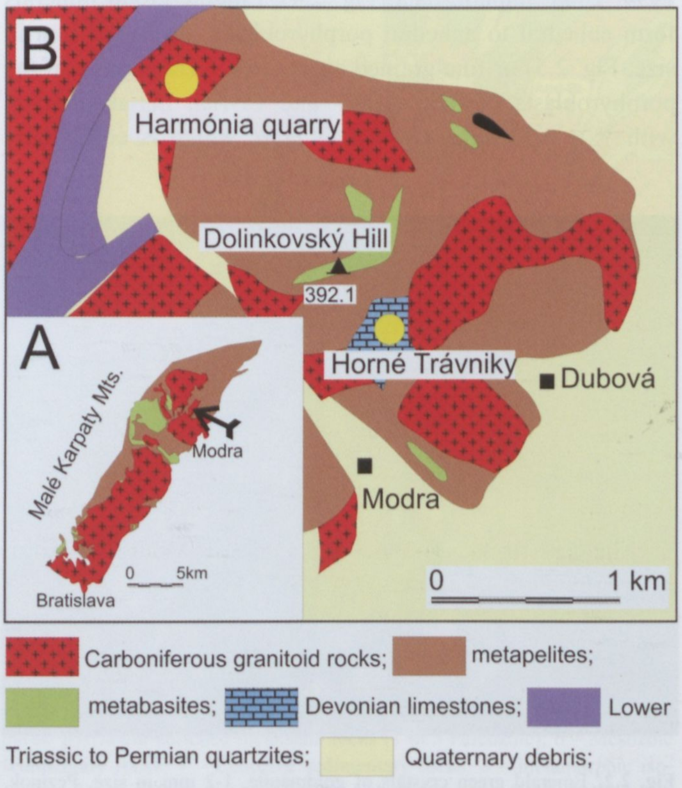


**Fig. 3.1.** Geological map showing the location of Harmónia quarry at Modra (Stop 3, Modra granitoid massif) and calc-silicate hornfels in Dubová, Horné Trávniky (Stop 4).

***Granitic rocks:*** The granitic rock that intruded metapelites to metapsammites in the Harmonia area is mainly light grey, medium-grained biotite granodiorite (locally tonalite) showing mineralogical and geochemical affinity to I-type granitoids. Thin aplite and pegmatite dikes cut the granodiorite (Fig. 3.2). Rock-forming minerals of the granodiorite are dominated by plagioclase (55 vol%) and anhedral quartz (30 vol%). K-feldspar (4 vol%) is interstitial, perthitic and locally encloses small plagioclase grains. Subhedral biotite (10 vol%) is in interstitial position among quartz and plagioclase and it shows incipient chloritization. Increase amount of black (dusky) apatite is typical of these granitic rocks, other accessory minerals comprise zircon, magnetite, titanite, allanite-(Ce) and epidote, confirming the I-type character of the granitic rock (Cambel & Vilinovič, 1987; Broska *et al.*, 2008). The chondrite normalized REE in granodiorite shows strongly prevailing of LREE over HREEs and negative Eu-anomaly. Zircon saturation temperature (Watson & Harrison, 1983) for the Modra granite is ~790 °C, monazite saturation temperature


**Fig. 3.2. (a)** Intrusive contact between the Modra granodiorite (G) and crystalline schists (M). **(b)** Pegmatite dike in granodiorite. Modra, Harmónia quarry. Photo: P. Uher.

according to Montel (1993) gives temperature estimates of 780 °C. The maximum pressure estimated from Al-in-hornblende thermobarometer is less than 150 MPa (Broska *et al.*, 2008).

The age of the granitic rocks of the Modra massif is Mississippian, based on hornblende K-Ar dating (Bagdasarjan *et al.*, 1977), monazite chemical dating (Finger *et al.*, 2003) and zircon SHRIMP dating (347 ± 4 Ma; Kohút *et al.*, 2009).

Petrochemistry of the Modra granitic massif shows its calc-alkaline character. The relatively high concentration of Sr and Ba in granodiorites is reflected also in their dikes. Dikes occurring in the area of the Dolinkovský vrch Hill (Fig. 3.1) intrude both metapelitic and carbonatic wall rocks. Those dikes in the metapelites and metabasites (10–15 meters in width) in the centres show syenogranitic to syenitic composition. Earlier authors considered them to be products of K-metasomatism, but a process of K-feldspars compaction due to flowage differentiation explain their origin. The Ba contents in the K-feldspars from dikes show a bell-shaped distribution indicating magmatic origin (not metasomatic) and pointing to fractionation of K-feldspar from the melt. The abundant apatite in syenite, enclosed mainly in interstitial quartz, is interpreted as a crystallizing phase in a Ca, Si and P rich boundary layer, adjacent to K-feldspars. The fractionation of amphibole, which present in some dikes, may have increased the A/CNK ratio to values exceeding 1.05 sufficient for the delay in apatite crystallization and enabling the growth of P in the system. In the following compaction, a quartz–albite melt was expelled, leaving a cumulate of K-feldspars with syenitic composition to various degrees enriched in K-feldspar and apatite. The dikes cutting the limestones show a wide contact aureola of calc-silicate hornfelses, suggesting an extensive fluid interaction between magma and wall rock.

***Cordierite schists:*** Formation of patchy cordierite-bearing hornfels (Fig. 3.3) and phyllitic schists within the contact

**Fig. 3.3.** Patchy hornfels with andalusite and altered cordierite from the contact aureola of the Modra granodiorite, Modra, Harmónia quarry. Specimen size: 5 cm. Photo: I. Broska.

aureole of the Modra massif suggests a shallow emplacement depth. The mobility of magma, which was able to ascent to shallow levels and created the contact metamorphism, was supported by its primarily low water content indicated by the biotite composition. Biotite is Mg-Ti-rich and its stability curve (Wones, 1972) suggests 2.2 wt% of water in the parent melt. Cordierite is preserved as small relics in low temperature muscovite. The contact aureole around the Modra massif referring to the andalusite–biotite–muscovite subfacies has been formed under conditions of higher temperature (up to 650 °C) and low $p$ (= 200 MPa) (Korikovsky *et al.*, 1985).

## 2.4 Field stop 4: Ca-skarn mineralization, Dubová, Horné Trávniky

**Locality:** Dubová, Horné Trávniky wineyards
**Geographical coordinates:** N 48°21.76′; E 17°18.54′

**Key words:** Malé Karpaty Mts., Ca-skarn, calc-silicate hornfels, Modra massif granite, aplite and pegmatite, grossular, vesuvianite, wollastonite, diopside, titanite, hyalophane, zircon

**Locality description:**

***Position:*** Outcrops of Ca skarns (erlans, calc-silicate hornfels) occur in a hillock above wineyards between Modra-Harmónia and Dubová villages (Fig. 4.1). Granite with aplite and pegmatite dikes occurs in the vicinity of skarn. The rocks belong to the Palaeozoic basement of the Tatric Superunit of the Central Western Carpathians.

***Calc-silicate skarn:*** Skarn and metamorphosed marly limestone form lens-shaped bodies within the phyllite, black shale and basaltic metavolcanic rock of the Dubová Formation (Harmónia Group). The stratigraphic position and the rare fossil content as well as the metacarbonate above the Lower Devonian metapelitic rocks point to Middle Devonian age (Cambel & Planderová, 1985). The metacarbonates are locally intruded by the Hercynian Modra massif tonalite–granodiorite and their leucogranitic, aplitic to pegmatitic derivates. Grossular, diopside, vesuvianite, wollastonite, epidote, titanite and calcite were described from the calc-silicate hornfels (Cambel, 1954; Čajková & Šamajová 1960; Šímová & Šamajová, 1979; Korikovskij *et al.*, 1985; Cambel *et al.*, 1989) – Figs. 4.2–4.3. Garnet (79–94 mol% grossular, 5–19 mol% andradite, 1–2 mol% pyrope + spessartine; Cambel *et al.*, 1989) forms up to 1 cm large porphyroblasts in calcite–quartz–diopside or vesuvianite–diopside(–wollastonite) matrix. Zoning in garnet composition is expressed by decreasing of Fe and Ti from core to rim. Ti-rich vesuvianite (2.5–5.5 wt% $TiO_2$, ~1–2 Ti *apfu*) associates with grossular, wollastonite, diopside and titanite. Vesuvianite shows fine oscillatory zoning; some zones contain up to 5.3 wt% $REE_2O_3$ (0.96 REE *apfu*; Ce>La,Nd,Pr>>Y,HREE), and rarely 0.3–1.8 wt% $ThO_2$ (0.03–0.21 Th *apfu*; Uher *et al.*, unpubl. data). Hyalophane forms 20–40 µm large subhedral to euhedral inclusions in vesuvianite; the Ba-feldspar contains 6–28 wt% BaO; 12–59 mol% celsian, 29–79 mol% orthoclase, 6–10 mol% albite and 2–4 mol% anorthite (Uher, unpubl. data). K-feldspar and albite form intergranular anhedral grains in association with vesuvianite, grossular and diopside; K-feldspar contains 0.6–0.9 wt% BaO and shows $Or_{94-97}Ab_{02-04}Cn_{01-02}An_{00}$ composition, while albite contains $Ab_{98-99}An_{01}$. Diopside inclusions in garnet are homogeneous, in contrast to diopside in matrix, where zoning with Fe enrichment in the outer part of grains appears (Gawęda & Kohút, 2007). The peak metamorphic assemblage indicates $p$ ~150–200 MPa pressure, and $T$ = 650 °C temperature with $X_{CO2}$ ~0.05–0.1 (Korikovsky *et al.*, 1985; Cambel *et al.*, 1989).

***Granitic dikes:*** Dikes that penetrated the Devonian limestone and metamorphosed them to Ca skarn or calc-silicate hornfels (erlans) have been strongly contaminated by the lime-

**Fig. 4.1.** Dubová, Horné Trávniky hillock above wineyards. Photo: P. Uher.

**Fig. 4.2.** Grossular (brownish red) in calcite. Ca skarn, Dubová, Horné Trávniky. Photo: M. Janák.

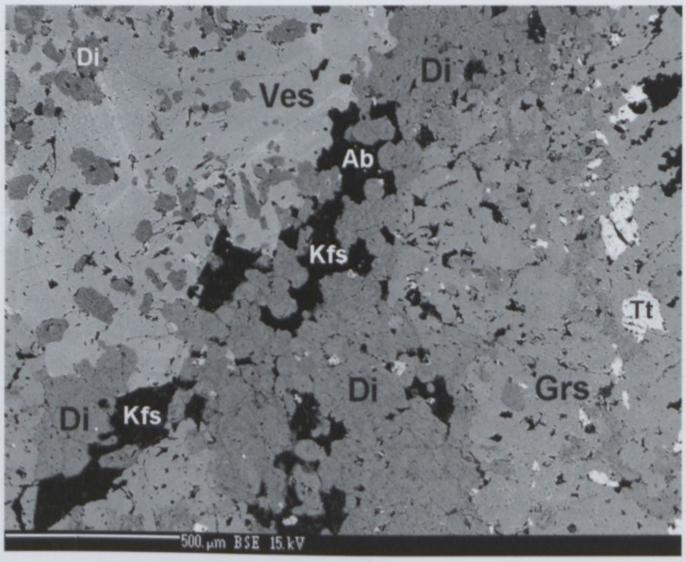


**Fig. 4.3.** Contact metamorphic assemblage of the Ca skarn, Dubová, Horné Trávniky. Diopside (Di), vesuvianite (Ves), grossular (Grs), albite (Ab), K-feldspar (Kfs) and titanite (Tt). BSE micrograph, photo: D. Ozdín.

stone. The surrounding limestone interacted with the magma at the time of intrusion and provided calcium to stabilise amphiboles. The euhedral amphibole (up to 10 vol%) forms 0.1–0.3 mm long crystals, which locally attains 2–3 cm in length due to recrystallization. Plagioclase (~50 vol%) is sericitized with wide albite rims, whereas K-feldspar, which is mostly interstitial and anhedral, shows perthitic structure. Quartz is interstitial. Accessory allanite-(Ce) is common in the form of euhedral crystals, locally replaced or overgrown by younger amphibole. The amphibole is commonly replaced by epidote, "Mg-phengite" and chlorite. Magnetite and dusky apatite are also present (Broska *et al.*, 2008). The leucogranitic to pegmatitic dikes in close contact with the skarn contain metamict hydrated zircon with dipyramidal shape. This zircon locally also contains domains of Th- and P-rich zircon and a Th- and P-dominant or a (Ca, Al)-rich intermediate phase (0.5–0.6 Th *apfu*, 0.3–0.4 Ca *apfu*, 0.1–0.2 Al *apfu*, 0.5–0.7 P *apfu*).

## Day 2

### 2.5 Field stop 5: Phosphate–sulphate mineralization, Bádice quarry

**Locality:** Bádice, quarry
**Geographical coordinates:** N 48°24.03′; E 18°08.17′
**Key words:** Tribeč Mts., metaquartzites, phosphates–sulphates, lazulite, barite, goedkenite, gorceixite, goyazite, crandallite, svanbergite, jarosite, (Ba, Fe, S, P)-phase, muscovite, fluid inclusions

**Locality description:**
***Position:*** The small abandoned quarry is situated on the SW part of the Tribeč Mountains, ~9 km NE of the town of Nitra (Fig. 5.1). The exposed rocks are metaquartzites with quartz veins of the Lúžna Formation (Fig. 5.2). They belong to the basement of the Tatric Superunit.

***Adjacent rocks:*** The rocks in the quarry are bedded, pale grey or white, fine to coarse-grained metaquartzite, rarely metaarkose with thin local intercalations of sandy slate of the Lúžna Formation. The metaquartzite is very silica-rich, it contains around 95 wt% $SiO_2$ in average. The metaarkose shows increased contents of K-feldspars and finely crystalline white mica (Ivanička, 1998). Basal layers are often coarse-grained monomict conglomerates with quartz pebbles. Planar cross-bedding and rippled lamination is preserved at some places. The sequence represents continental sediments of braided rivers (Mišík & Jablonský, 2000), which deposited on Hercynian granitic rocks of the Tribeč–Zobor massif. Accurate age of the Lúžna Fm. sedimentation is unknown due to scarcity of fossil record, however their Lower Triassic or Permoscythian age is proposed by superposition and analogy to similar sequences in the Eastern Alps (*e.g.* Semmering quartzite). The rocks were overprinted by an Eo-Alpine (Cretaceous) very low to low-grade metamorphism. The estimated peak metamorphic conditions of the rocks using the Kübler index of phyllosilicates point to anchizone/epizone boundary, *i.e.* ~270-350 °C (Uher *et al.*, 2009).

***Phosphate–sulphate mineralization:*** the Bádice quarry represents a typical example of the phosphate–sulphate mineralization of quartz veins in metaquartzite. The mineralization is known from over 30 localities of the Lúžna Fm. metaquartzite of the Tribeč Mountains (see *e.g.*, Sekanina, 1957; Jahn, 1976; Doubek & Jahn, 1987; Uher *et al.*, 2009). The mineralization comprises lazulite, (Ba, Sr, Ca, K)-rich phosphates–sulphates and barite in an association with muscovite, hematite, locally rutile, zircon, chlorite and tourmaline (Figs. 5.3–5.4). The most widespread lazulite forms up to 10-cm large pale to deep blue aggregates in massive quartz (Fig. 5.3). Electron-microprobe analyses show relatively uniform compositions with Mg/(Mg + Fe) = 0.85 to 0.93 (Fig. 5.5).

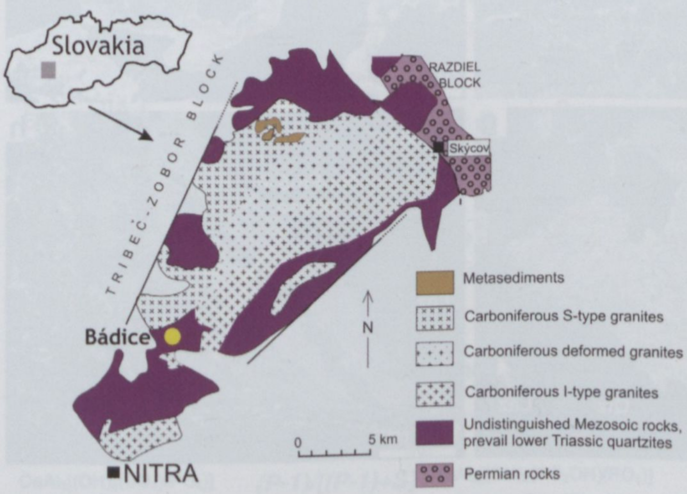


**Fig. 5.1.** Geological sketch of the Tribeč Mountains (Ivanička *et al.*, 1997, adapted) with the location of the Bádice quarry.

**Fig. 5.2.** Outcrop of metaquartzite with quartz vein and phoshate–sulphate mineralization (in the yellow rectangle). Bádice quarry. Photo: P. Uher.

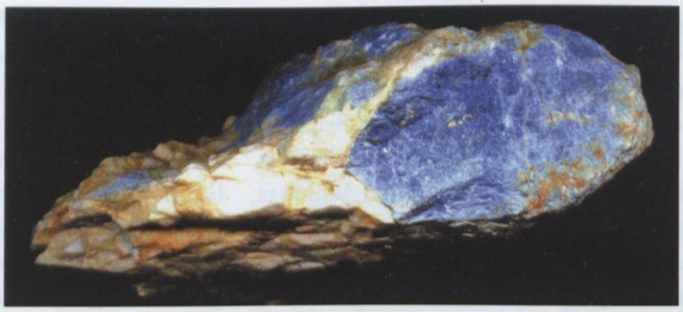

**Fig. 5.3.** Blue lazulite aggregate in white quartz. Specimen length 7 cm. Jelenec quarry, Tribeč Mts. Photo: P. Uher.

Results of Mössbauer spectroscopy studies revealed 11–30% $Fe^{3+}/Fe_{total}$. Goedkenite–bearthite binary *s.s.* shows the highest known Sr contents worldwide: Sr/(Sr + Ca) = 0.67–0.71; Mg, Ba and REE contents are negligible. The lazulite is replaced by secondary association of the (Ba, Sr, Ca, K)-rich phosphates–sulphates: gorceixite, rarely goyazite, crandallite, svanbergite, goedkenite, jarosite and a rare Ba-Fe-S-P phase, close to $(Ba,K,Sr)(Fe^{3+},Al)_3[(OH)_6(PO_4)(SO_4)]$ composition (Fig. 5.4). Gorceixite exhibits more restricted compositional variations between gorceixite–goyazite and gorceixite–crandallite *s.s.*: Ba/(Ba + Sr) = 0.73–0.99, Ba/(Ba + Ca) = 0.78–0.99 and (P–1)/[(P–1) + S] = 0.84–0.99 (Fig. 5.6). On the contrary, the secondary (Sr, Ca)-dominant phosphates–sulphates of the crandallite and beudantite groups show wide compositional variations and complex quarternary solid-solution series between goyazite–crandallite and svanbergite–woodhouseite with Sr/(Sr + Ca) = 0.16 to 0.99 and (P–1)/[(P–1) + S] = 0.07 to 0.97 (Fig. 5.6). The (K, Ba)-dominant phosphates–sulphates of the alunite and beudantite groups occur along the jarosite–Ba-Fe-S-P phase *s.s.* line with Ba/(Ba + K) = 0.07 to 0.56, Fe/(Fe + Al) = 0.55 to 0.99, P/(P + S) = 0.14 to 0.57 and elevated Sr and Ca; up to 0.24 and 0.12 *apfu*, respectively (Uher *et al.*, 2009). The compositions indicate close relationships and mutual substitutions between the crandallite, beudantite and alunite groups. Unlike to analogous phosphate-bearing assemblages in the Alps, the phosphate–sulphate association of the Bádice quarry doesn't contains REE, Y and Sc minerals but it is rich in Ba-containing phases (barite, gorceixite). Fluid inclusions study constrained the minimum formation temperature of the lazulite to 144–257 °C and of the superimposed phosphate–sulphate mineralization to 175–289 °C; lazulite crystallized from brines of the system $H_2O$–Na–Mg–Cl–$CO_2$ with salinities from 17.2 to 19.8

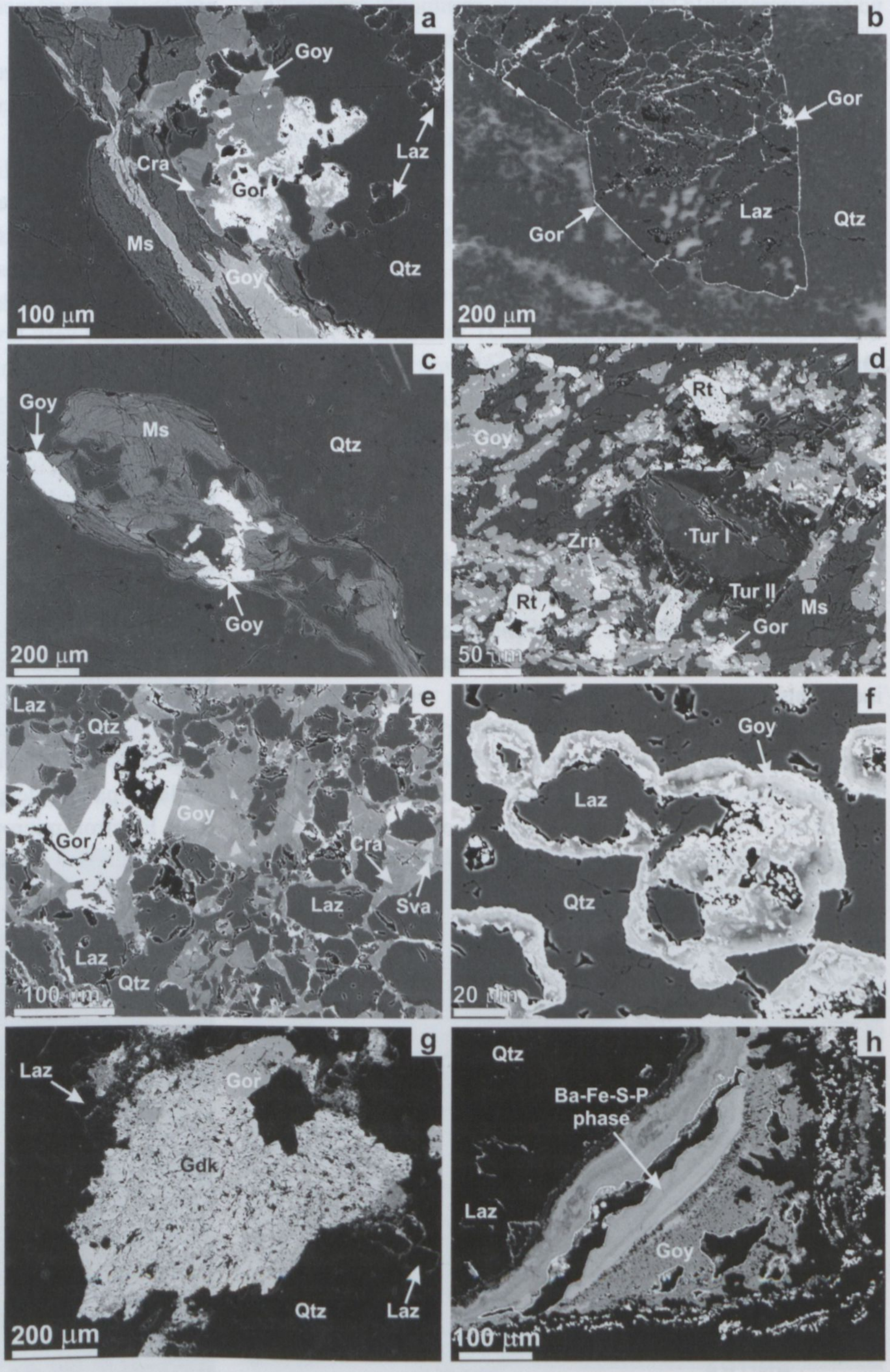


**Fig. 5.4.** BSE photomicrographs of lazulite (Laz) and associated gorceixite (Gor), goyazite (Goy), crandallite (Cra), svanbergite (Sva), goedkenite (Gdk), Ba-Fe-S-P-phase, muscovite (Ms), tourmaline (Tur), zircon (Zrn), rutile (Rt) in quartz (Qtz). Tribeč Mts. Photo: D. Ozdín.

wt% NaCl eq. (Uher *et al.*, 2009). The mineralization precipitated probably from fluids enriched in elements from breakdown of feldspars, biotite, apatite and other phosphates in underlying Hercynian granites, passing upwards into the metaquartzite and precipitated in the quartz veins (Uher *et al.*, 2009).

## 2.6 Field stop 6: Cu mineralization, Ľubietová, Podlipa

**Locality:** Ľubietová, Podlipa deposit
**Geographical coordinates:** N 48°44.78′; E 19°23.03′
**Key words:** Vepor Mts., Cu-mineralization, libethenite, euchroite, mrázekite, pseudomalachite, ludjibaite, reichenbachite, malachite

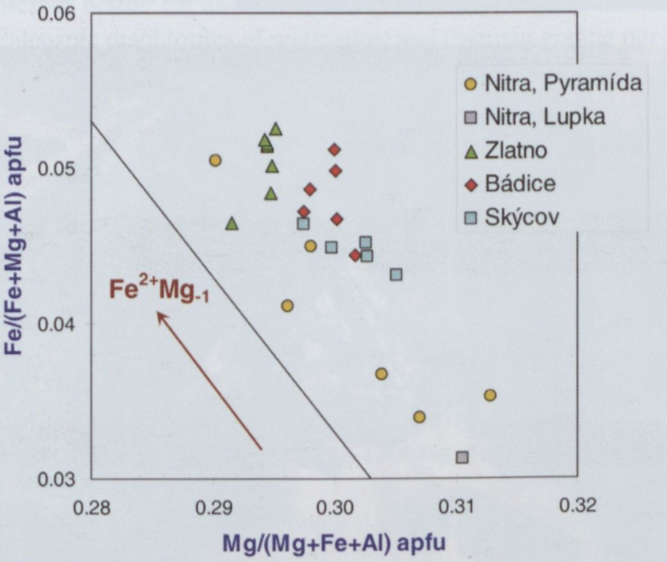


**Fig. 5.5.** Lazulite composition from the phosphate–sulphate mineralization in the Tribeč Mountains.

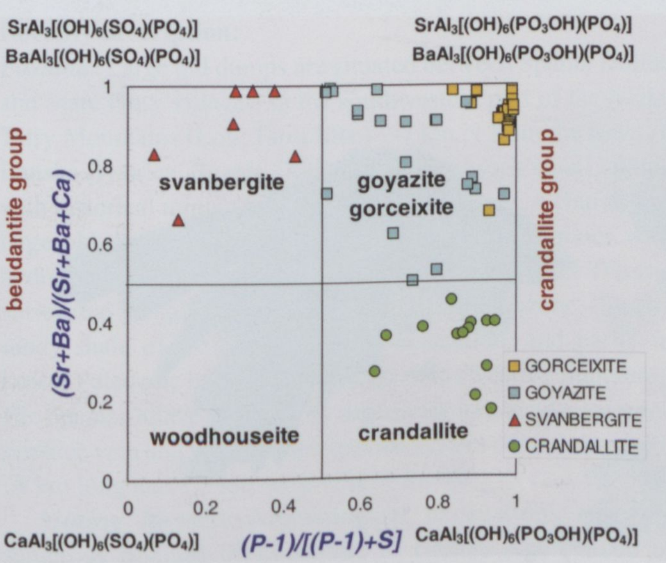


**Fig. 5.6.** Composition of (Ba,Sr,Ca) phosphates–sulphates from the Tribeč Mountains.

**Locality description:**

***Position:*** Large dumps of abandoned copper mines with primary sulphide and famous secondary copper minerals are situated in the area of the historic former royal mining town, ~15 km east from the town of Banská Bystrica (Fig. 6.1). The hydrothermal Cu mineralization occurs in three deposits: Podlipa, Svätodušná and Kolba. Ľubietová is the type locality of libethenite, euchroite and mrázekite. Host rocks of the mineralization are Permian metasandstones, greywackes, arcose schists and arcoses, locally shales and conglomerates of the Predajná Formation. Pebbles of quartz, granite and migmatite are from the underlying dynamically metamorphosed Vepor crystalline complex. Lower Paleozoic micaschists and Permian acid metavolcanic rocks and granite porphyries occur in the vicinity. The rocks and mineralization belong to the Paleozoic basement and their metasedimentary cover of the Veporic Superunit.

***Mining history:*** According to archeological data, copper has been exploited since the Bronze Age. At that time, the native copper from upper horizon was mined. The initial written mention of mining in Ľubietová comes from the Anjou era of the Hungarian Kingdom in 1340, indicating that in addition to copper, gold was gained in minor amount. Mining boom has been lasted for 200 years, in the 15$^{th}$ and 16$^{th}$ centuries, whereas iron production started in the 18$^{th}$ century. Mining has been finished in 1863. Prospecting for copper ore during second part of 20$^{th}$ century was not successful (Koděra *et al.*, 1990).

***The Podlipa deposit*** is situated ~1 km east from the middle of village, on the southern slope of the Vysoká Hill (995.5 m altitude). Principal tectonic lineaments show directions NE–SW, but main veins follow E–W or N–S direction with 50° incline. Primary ore-bearing veins, bunch or clusters, lenses and impregnation zones attain thickness up to 40 m. The main ore mineral is chalcopyrite, with less amount of pyrite. In the deeper parts of mineralization, amount of tetraedrite

**Fig. 6.1.** Old dumps in Ľubietová, Podlipa deposit. Photo: P. Uher.

increases, galena is rare. Locally, cassiterite inclusions were identified in chalcopyrite (Ozdín, oral comm.). The quartz gangue often encloses siderite, ankerite and barite. Siderite–sulphide parts of the deposit show stockwork or disseminated character; the stockwork zones are known in the southern parts of deposit. Rarely, black tourmaline of schorl composition associates with quartz. Origin of the primary ores is probably connected with Permian volcanic activity and mineralization is volcano-sedimentary or stratiform origin. The Permian ores have been intensively remobilised, dissolved and reprecipitated during the Alpine orogenesis. In the past, cuprite and native copper were appeared in upper oxidation and cementation zone (Koděra *et al.*, 1990). The Podlipa deposit contains 18 galleries between 570 to 700 m altitude, from the lower Maria Empfängnis to uppermost Francisci adit. The copper content of ore ranges from 4 to 10%, and exceptionally up to 22% in the Klement adit. The Nepomuk vein contains 7.66% Cu, 70 g/t Ag and minor gold. Mines on the Podlipa deposit were extensively oxidised, only lower part contains sulphide in higher concentration. The best commercial ore mineralization has been exploited in the level of the Nepomuk adit. Around 25,000 t of copper has been mined from Podlipa deposit during the 500 years history of mining.

The most famous minerals of the locality are the secondary Cu phases, especially phosphate minerals. Two new minerals were described from the Podlipa deposit: libethenite, $Cu^{2+}_2[(OH)(PO_4)]$ (after Libethen, German name of Ľubietová; Leonhard, 1812 and Breithaupt, 1823 in Koděra *et al.*, 1990; Papp, 2004), and mrázekite, $Bi_2Cu^{2+}_3[O(OH)(PO_4)]_2 \cdot 2H_2O$ from Reiner gallery (Řídkošil *et al.*, 1992). Libethenite forms deep green octahedral crystals with adamantine luster, 1–2 mm, up to max. 1 cm in size, in quartz fissures or in association with pseudomalachite, malachite and goethite (Figs. 6.2–6.3). Mrázekite occurs as blue acicular crystals, up to 3 mm in length in small rock fissures (Fig. 6.4). Pseudomalachite, $Cu_5[(OH)_4(PO_4)_2]$ is a characteristic mineral in the Podlipa deposit: it forms usually irregular dark green crusts. Malachite forms aggregates of acicular crystals or radiating aggregates. Moreover, reichenbachite and ludjibaite, two other rare $Cu_5[(OH)_4(PO_4)_2]$ modifications, have been found occur on dumps of the Reiner gallery (Hyršl, 1991). In addition, cyanotrichite, brochantite, chysocolla, tirolite and langite were described from the Podlipa deposit (Čech & Láznička, 1965; Povondra & Řídkošil, 1980; Řídkošil, 1982; Koděra *et al.*, 1990; Pauliš & Ďuďa, 2002).

***Svätodušná Deposit (Svätoduška)*** is the second largest deposit at Ľubietová. The deposit is located in the Peklo valley, 5 km E from Ľubietová village. Mineralization occurs in diaphtoritic migmatites and micaschists close to a geological boundary to Permian granite porphyry rocks. Veins contain magnesite, siderite, quartz, tourmaline, tennantite, chalcopyrite and cobaltite. There is a varied paragenesis of secondary Cu minerals, especially arsenates; their occurence is connected with presence of arsenopyrite and gersdorffite in primary

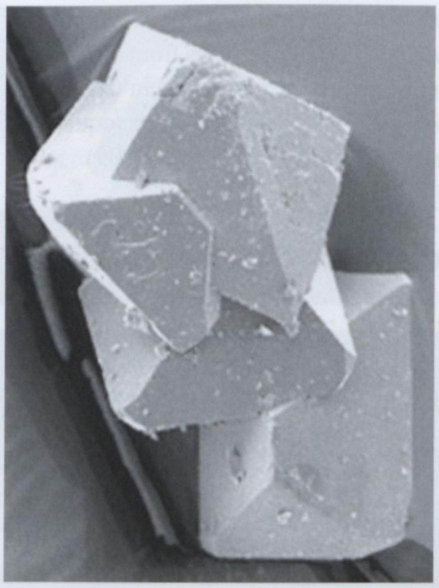

**Fig. 6.2.** SEM photomicrograph of libethenite crystals, Ľubietová, Podlipa. Crystal size 0.5 mm. Photo: I. Holický.

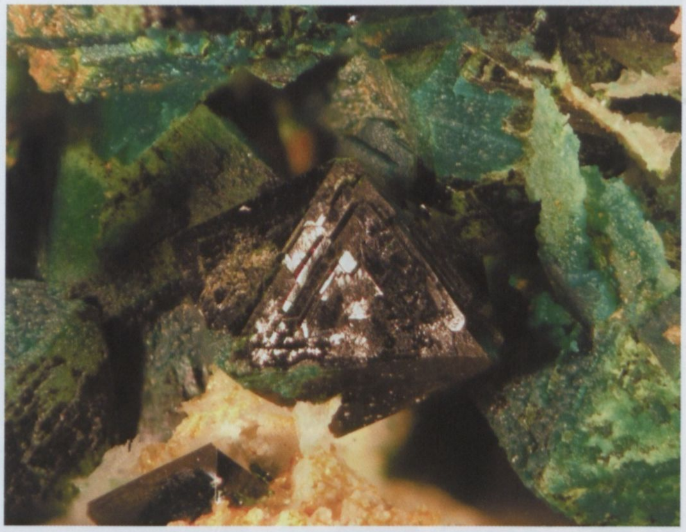

**Fig. 6.3.** Libethenite crystal, Ľubietová, Podlipa. Field of view 8 mm. Photo: M. Števko.

**Fig. 6.4.** Blue mrázekite crystals on quartz. Ľubietová, Podlipa. Crystal size: 1-2 mm. Photo: M. Števko.

ores. Euchroite, $Cu^{2+}_2[(OH)(AsO_4)]\ 3H_2O$, was described here as a new mineral (Breithaupt, 1823 in Koděra *et al.*; Papp, 2004); it forms green prismatic crystals up to 2 cm in size. Other secondary phases comprise olivenite, pharmacosiderite, annabergite, brochantite, pseudomalachite, tirolite, strashimirite, clinoclase, aurichalcite, chalcophyllite and erythrite (Doubek & Malec, 1977; Pauliš, 1981; Řídkošil & Medek, 1981; Koděra *et al.*, 1990; Pauliš & Ďuďa, 2002). Recently, other rare secondary Cu phases have been discovered: deep green incrustation of cornubite, green crystaline crusts of parnauite (Sejkora, 1993), pale blue acicular aggregates of chalcoalumite and light blue shattuckite (Ondruš & Veselovský in Pauliš & Ďuďa, 2002).

***The Kolba deposit*** is situated at the termination of Peklo valley, ~6.5 km E from the village of Ľubietová, where a significant occurrence of Co, Ag and Ni mineralization is also present beside Cu and Fe. The deposit is built up by Lower Paleozoic diaphtorites of migmatites and Permian granite porphyries. The tectonic structures that contain the ore mineralization show NE–SW direction and steep inclination. Veins form a system of ore lenses of several tens cm in thickness. Veins filling consists of carbonates, quartz, tourmaline, chlorite, arsenopyrite, pyrite, cobaltite, tennantite, skutterudite and chalcopyrite (Koděra *et al.*, 1990). Secondary mineralization is relatively weak in comparison to previous deposits but erythrite is abundant.

## 2.7 Field stop 7: Hydrothermal and secondary mineralization, Špania Dolina deposit

**Locality:** Špania Dolina, copper deposit
**Geographical coordinates:** N 48°48.46′; E 19°07.98′
**Key words:** Nízke Tatry Mts., Cu-mineralization, devilline, malachite, azurite, celestite, aragonite

**Locality description:**

***Position:*** Large old dumps are situated between Špania Dolina and Staré Hory villages, in the southwestern part of the Nízke Tatry Mountains (Low Tatra Mts.), ~7 km N from the town of Banská Bystrica. Špania Dolina is a picturesque small village with historical mining buildings, miner's houses, a church and large old dumps (Figs. 7.1–7.2). The abandoned mines with hydrothermal Cu ores partly lies in Permian to Lower Triassic variegated conglomerate, coarse-grained sandstone, locally sandy shale of the Špania Dolina Formation, and partly in Lower Paleozoic banded orthogneiss of the Veporic Superunit. The Špania Dolina – Staré Hory deposit forms a quartz–siderite–sulphide vein and veinlet-impregnation system of N–S direction, ~4 km long and 1.5 km wide (Fig. 7.3).

***Mining history:*** Archeological excavations revealed numerous findings of Eneolithic to Bronze Age (~3000 to 1500 BC), stony tools for crushing of copper ore, which document one of the oldest ore mining activity in Europe. Medieval exploitation of Fe, Cu and Ag ores has been recorded since the 13th century with a maximal production in 16–17th centuries, when the mines belonged to the Fugger and Thurzó

**Fig. 7.1.** Špania Dolina village. Photo: S. Jeleň.

**Fig. 7.2.** Large old dumps at Špania Dolina, Piesky. Photo: S. Jeleň.

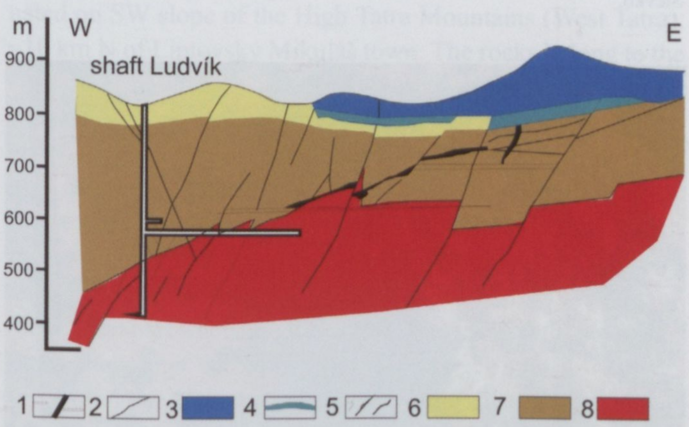


**Fig. 7.3.** Geological cross-section of the Špania Dolina copper deposit in the vicinity of Ludvík shaft (based on Pecho *et al.* in Slávik, 1967). 1 – mining work; 2 – faults; 3 – Triassic dolomite; 4 – Lower Triassic schist and limestone; 5 – ore-bearing zones; 6 – Lower Triassic sandstones; 7 – Permian sedimentary rocks; 8 – Lower Palaeozoic granite and orthogneiss.

families. Around 67,000 metric tons of copper was exploited from the Špania Dolina deposit until the 20th century; the ore contained 8–15% Cu and 0.01–0.03% Ag (Koděra *et al.*, 1990). The latest small exploitation of Cu ores from dumps was active from 1964 to 1986.

**Minerals:** White massive quartz is the dominant primary hydrothermal mineral, and it is associated with common siderite, rarely ankerite and dolomite aggregates. Chalcopyrite, tetrahedrite and pyrite are the most widespread sulphide minerals; tetrahedrite locally forms up to 5-mm large crystals. Galena, sphalerite, stibnite, arsenopyrite, pyrrhotite, marcasite, and aikinite belong to subordinate sulphide phases together with native gold (Koděra *et al.*, 1990; Pauliš & Ďuďa, 2002). Calcite, aragonite, celestine, barite, anhydrite, and gypsum belong to the latest low-temperature hydrothermal minerals. Famous are historical findings of white aragonite crystals (twins, trillings and sixlings, up to 10 cm long), which form large druses; an almost 6-m large aragonite druse was found here in 1840 (Pauliš & Ďuďa, 2002). Moreover, pale blue celestine crystals on calcite (up to 15 mm long) attain superb quality (Fig. 7.4).

The Špania Dolina – Staré Hory hydrothermal deposit contains a well-developed cementation and oxidation zone with plenty of secondary Cu minerals (Figs. 7.5–7.7). Azurite and malachite are the most widespread, they form common incrustations and small crystals in vugs, locally up to 15 cm thick malachite masses. Rare cuprite and native copper associate with malachite. Secondary devilline (described from here as a new mineral named "herrengrundite" by Brezina, 1879, or "úrvölgyite" by Szabó, 1880, and Winkler, 1880, see Koděra *et al.*, 1990 and Papp, 2004) forms thin lamellar blue-green crystals, up to 1 cm large. Other typical secondary minerals of the Špania Dolina – Staré Hory deposit comprise langite, posnjakite, chalcophyllite, tirolite, barium-pharmacosiderite, brochantite, camerolaite, aurichalcite, antlerite, liroconite, bayldonite, chalcantite, olivenite, pseudomalachite, chrysocolla, bornite, covellite, chalcocite, tenorite, jarosite, bindheimite, erythrite, realgar, epsomite, goslarite, melanterite, allophane, pyrophyllite, dawsonite, native sulphur, hematite, and goethite (Figuschová, 1978; Povondra & Řídkošil, 1980; Řídkošil & Povondra, 1982; Blaha, 1983; Koděra *et al.*, 1990; Pauliš & Ďuďa, 2002).

**Fig. 7.4.** Celestine crystals, size up to 4 mm. Špania Dolina. Photo: M. Števko.

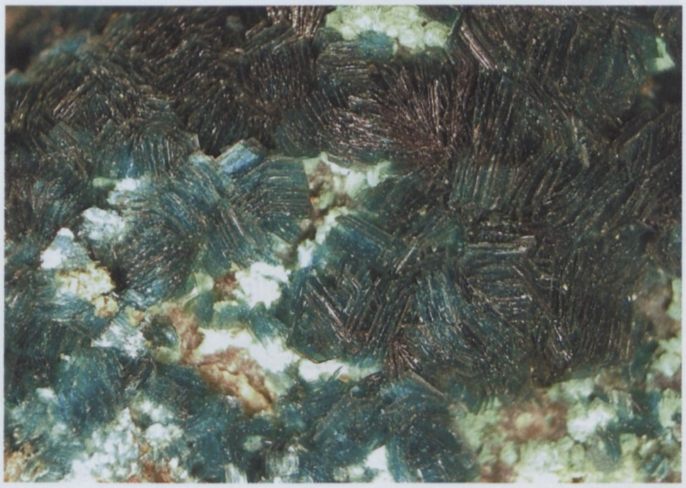

**Fig. 7.6.** Aggregates of tabular devilline crystals, Crystal size 3-4 mm. Špania Dolina. Photo: M. Števko.

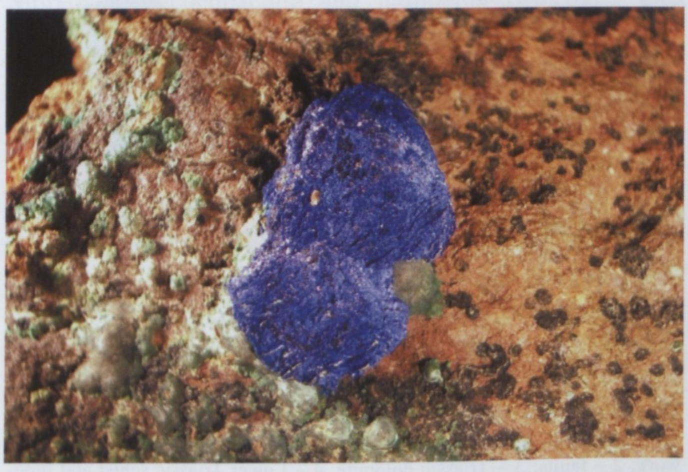

**Fig. 7.5.** Azurite aggregate, size 7 mm. Špania Dolina. Photo: M. Števko.

**Fig. 7.7.** Native copper dendrites in the host rock, Size of the dendrites: up to 1 cm. Špania Dolina. Photo: S. Jeleň.

# Day 3 (Wednesday, 18 August 2010)

## 2.8 Field stop 8: Travertine terraces, Bešeňová

**Locality:** Bešeňová, travertine terraces
**Geographical coordinates:** N 49°06.24′; E 19°11.22′
**Key words:** Liptov basin, travertine, calcite, Pleistocene, aquifer

**Locality description:**

***Position:*** A large stack of recent travertine occurs in Bešeňová village, near Liptovský Mikuláš town, in northern Slovakia. Beatiful panoramatic view to the basin is very nice in fine weather. The Liptov basin belongs to an Alpine depression between the High and Low Tatra, filled mainly by Palaeogene flysch sediments of the Central Western Carpathians.

***Travertine:*** The village of Bešeňová is well known by occurrences of Quaternary (Pleistocene) "freshwater" travertine terraces. The Bešeňová Travertines Natural Monument spreads to an area of 3.18 ha. The cascades of this exquisite limestone formation are fresh and shiny, thanks to the water discharge, which continuously streams down (Fig. 8.1). This water does not contain only calcium but also magnesium, sulphur and iron. That is why the travertine terraces in Bešeňová are extraordinarily colourful (Fig. 8.2).

**Fig. 8.1.** Recent mineral spring at Bešeňová creating "new travertine". Photo: I. Broska.

Geothermal water aquifers in the Liptov basin are located in Triassic dolomites and limestones with fissure karst permeability, which were documented by geothermal boreholes at depth from 1250 to 1650 m. Their thickness varies between 300 and 1000 m.

The gas bubble point (where hydrostatic pressure is equal to atmospheric) in the boreholes of Liptov basin is in the interval 160–200 m. Some springs are forming the travertine. The borehole for Bešeňová aquapark was drilled in 1986 and reached the depth of 1986 m.

**Fig. 8.2.** Travertine terraces at Bešeňová. Photo: I. Broska.

The travertine was used for producing of golden yellow slabs, used for the decoration many buildings, *e.g.* of the Comenius University in Bratislava, or the Palace of Nations in Geneva.

## 2.9 Field stop 9: Banded amphibolites and metapelites, Žiarska dolina valley (Žiar valley)

**Locality:** Žiarska dolina valley (Tatra National Park), banded amphibolite and metapelite
**Geographical coordinates:** N 49°08.78′; E 19°42.11′
**Key words:** Tatra Mts., banded amphibolite, micaschists, Variscan metamorphism, retrogressed eclogite, geochronological dating

**Locality description:**

***Position:*** Outcrops along the cliffs on the steep slopes of the Žiarska dolina valley above the forest road. The locality is situated on SW slope of the High Tatra Mountains (West Tatra), ~10 km N of Liptovský Mikuláš town. The rocks belong to the Paleozoic basement of Tatric Superunit, Central Western Carpathians.

***Geological setting:*** The crystalline basement of the Tatra Mts. (Fig. 9.1) is composed of pre-Mesozoic metamorphic rocks and granite, overlain by Mesozoic and Cenozoic sedimentary cover sequences and nappes. Metamorphic rocks are abundant in the western part (the West Tatra Mts.), whereas in the eastern part (the High Tatra Mts.) they form only xenoliths in granites (Figs. 9.1–9.2).

Within the basement, two superimposed tectonic units – lower and upper, differing in lithology and metamorphic grade, have been distinguished (Janák, 1994). These units are separated by a thrust fault – a major tectonic discontinuity in the crystalline basement of the Tatra Mountains (Figs. 9.1–9.2).

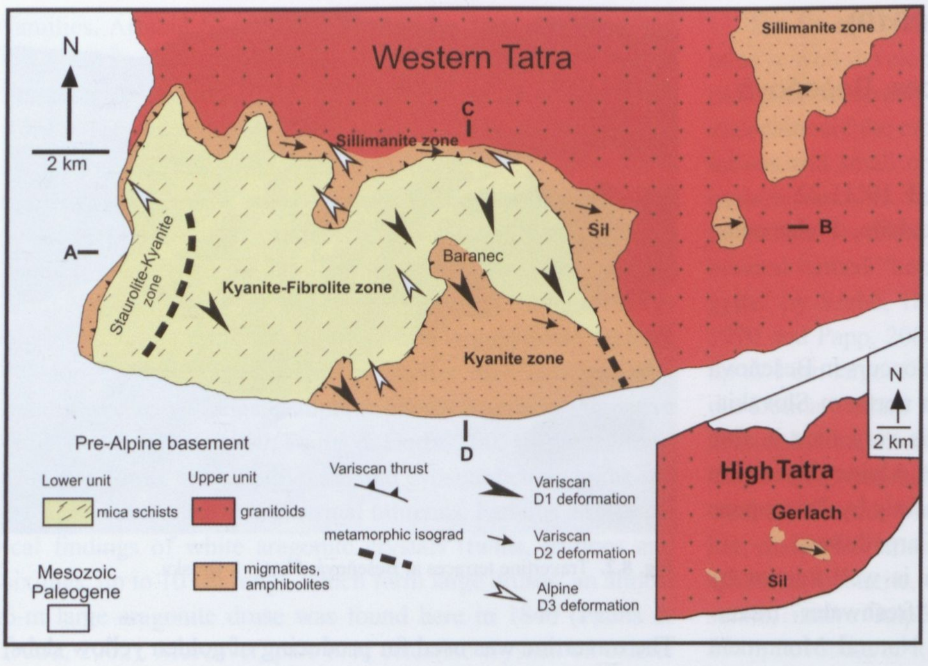


**Fig. 9.1.** Simplified geological map with the metamorphic zones of the Tatra Mts. crystalline basement.

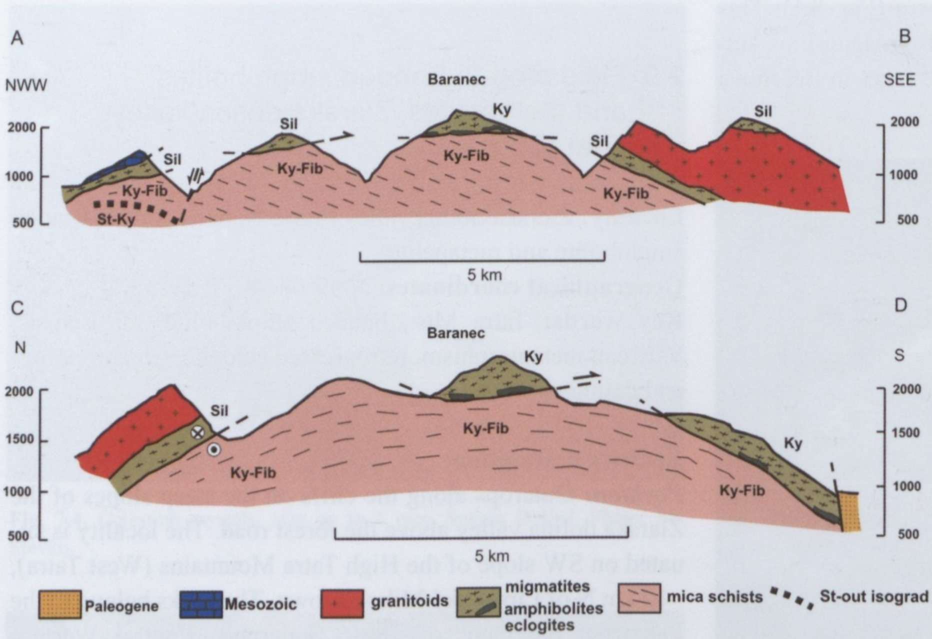


**Fig. 9.2.** Garnet-bearing banded amphibolite, Žiarska Valley. Photo: M. Janák.

The *Lower unit* is exposed in the Western Tatra in a tectonic window with up to 1000-m thickness (Figs. 9.1–9.2); it is composed of micaschist. Kyanite-, staurolite-, fibrolitic sillimanite- and garnet-bearing metapelite alternates with quartz-rich metapsammite, indicating former flysch sediments (Kahan, 1969). The staurolite–kyanite and kyanite–sillimanite (fibrolite) zones are separated by the staurolite-out isograd (Figs. 9.1–9.2).

The *Upper unit* is composed of migmatite and granite. Relics of high-pressure metamorphism (eclogite) occur in amphibolite at the base of the upper unit (Fig. 9.2). The amphibolite is banded, with layers of mafic (amphibolite) and felsic (tonalitic to trondhjemitic) composition alternating on mm to dm scale. They enclose lenses (several dm to m) of eclogitic relics with garnet and clinopyroxene (Janák *et al.*, 1996). Metapelites with kyanite show incipient migmatization and formation of granite leucosomes. Orthogneisses are mylonitic with augen-like porphyroclasts of K-feldspar. Higher levels of the upper unit (sillimanite zone) are intruded by a sheet-like granite pluton (Gorek, 1959), whose composition ranges from leucogranite to biotite tonalite and amphibole diorite (Kohút & Janák, 1994). In associated metapelite, migmatisation is ubiquitous and prismatic sillimanite together with garnet; K-feldspar and cordierite are diagnostic minerals. Amphibolite contains garnet, but eclogitic relics are not preserved.

**Geochronological dating:** The oldest tectono-metamorphic event in the Tatra Mountains seems to be Early Devonian, 406 Ma, according to the zircon single grain data from orthogneiss (Poller *et al.*, 2000). Major granite magmatism took place in Late Devonian and Carboniferous time (~360–340 Ma) according to U-Pb single-zircon data (Poller *et al.*, 1999, 2000). The $^{40}$Ar-$^{39}$Ar ages of biotite and muscovite from granitoids and metamorphic rocks (330–300 Ma), obtained by both step-heating (Maluski *et al.*, 1993) and laser ablation (Janák & Onstott, 1993; Janák, 1994) methods, record a cooling and uplift during Late Variscan time. Apatite fission track data record the final uplift during the Tertiary, at 15-10 Ma (Kováč *et al.*, 1994).

***Metamorphism:*** Metapelite in the lower unit contain kyanite ± staurolite + fibrolitic sillimanite + garnet + biotite + muscovite I ± chlorite I + plagioclase + quartz assemblages. Relics of rutile are sporadically present and ilmenite is more abundant. Staurolite is abundant in the staurolite– kyanite zone exposed in the westernmost part of the Tatra Mts. (Figs. 9.1–9.2). Kyanite and fibrolitic sillimanite are diagnostic minerals of the kyanite–sillimanite (fibrolite) zone where staurolite relics appear sporadically. As inferred from metamorphic textures, fibrolitic sillimanite is a relatively younger phase than staurolite and kyanite. Later retrograde overprint is demonstrated by the formation of chlorite II, chloritoid, margarite and muscovite II in the microfractures and pseudomorphs after staurolite, kyanite and garnet. Metamorphic *p–T* conditions from about 550–620 °C temperature and 5–6 kbar pressure in the staurolite–kyanite zone to 620–660 °C temperature and 6–8 kbar pressure in the kyanite–sillimanite (fibrolite) zone have been calculated (Janák *et al.*, 1988; Janák, 1994).

Metapelite in the upper unit contains the following mineral assemblages: garnet + kyanite ± sillimanite + biotite + plagioclase ± K-feldspar ± muscovite with staurolite relics, and garnet + sillimanite + biotite + quartz + plagioclase ± K-feldspar ± muscovite; or biotite + sillimanite + cordierite ±garnet + quartz + plagioclase ± K-feldspar ± muscovite in the sillimanite zone. Ilmenite, rutile and magnetite represent Fe-Ti oxides. Minor and accessory minerals include orthoamphibole (gedrite, anthophyllite), chlorite, epidote, carbonates (calcite, siderite), zircon, monazite and apatite. Retrogression led locally to the origin of chloritoid, muscovite, margarite and chlorite in late fractures. The leucosome formation in the metapelitic migmatites resulted from the dehydration melting of muscovite and biotite (Janák *et al.*, 1999). Decompression from a high-pressure stage (12–14 kbar) led to the transformation of kyanite to sillimanite. Locally (area of Ježová), cordierite have been formed at ~4–5 kbar (Ludhová & Janák, 1999). A $CO_2$-rich fluid was generated during the interaction of melt-derived water with metapelite graphite (Janák *et al.*, 1999; Hurai *et al.*, 2000). Consequently, high-grade peak metamorphic assemblages have been strongly obliterated by retrogression at subsolidus conditions.

Metabasite with garnet and clinopyroxene occurs in the kyanite zone and shows symplectitic (diopside + plagioclase) and kelyphitic (amphibole + plagioclase) textures. Thermobarometric calculations from mineral inclusions in the garnet cores yielded 670–700 °C temperature and 10–15 kbar pressure recording the initial path from amphibolite to eclogite facies conditions (Janák *et al.*, 1996). The symplectites have formed by breakdown of omphacite, suggesting extensive re-equilibration of eclogite in the amphibolite/granulite facies conditions (650–750 °C; 8–12 kbar) during exhumation. Several generations of amphibole (pargasite, hornblende, cummingtonite, actinolite) are evidence of a transformation down to greenschist facies conditions. Fluid inclusions in quartz contain nitrogen-dominated, water-absent fluids similar to those reported from typical high-pressure eclogites (Janák *et al.*, 1996; Hurai *et al.*, 2000). Presence of tonalitic and trondhjemitic veins suggests partial melting in metabasites. In the sillimanite zone metabasite, relics referring to high-pressure conditions are lacking.

As inferred from spatial distribution of metamorphic zones and mineral assemblages in the upper unit, the highest-pressure conditions have been attained at the base of the unit, while the upper levels reveal metamorphic recrystallization at lower pressure conditions.

## Stop 9A

*Rocks*: Micaschist of the kyanite–sillimanite (fibrolite zone) in the lower tectonic unit, close to the contact with the upper unit.

*Location*: Western Tatra Mts., Žiarska dolina valley (Žiar valley) – middle part, exposures ~1500 m on the road towards the Žiarska chalet.

Outcrops in the Žiarska dolina valley expose the micaschists of the kyanite–sillimanite (fibrolite) zone beneath the thrust contact. Mineral assemblage in metapelite contains kyanite, garnet, fibrolitic sillimanite, biotite, muscovite, plagioclase, rutile, ilmenite and quartz. *p–T* conditions of metamorphism reached 620–640 °C temperature and 6–7 kbar pressure.

## Stop 9B

*Rocks:* banded amphibolite and orthogneiss, HP–HT metamorphism and deformation at the base of the upper unit.

*Location*: Western Tatra Mts., Žiarska dolina valley (Žiar valley) – lower part, rock exposures ~30–50 m above the road to Žiarska chalet.

**Fig. 9.3.** Banded amphibolite, Žiarska Valley. Photo: M. Janák.

Banded amphibolite forms the characteristic lithology, and marks the detachment plane of the upper (overthrust) unit. Mafic layers consist of amphibole (hornblende to pargasite) and plagioclase, with minor quartz, ilmenite, rutile and titanite. Leucocratic bands are composed predominantly of plagioclase (oligoclase), quartz and almandine garnet (Fig. 9.3).

Orthogneisses are coarse-grained with augen-like K-feldspars of 1–2 cm size, or fine-grained, foliated, with distinctive mylonitic fabric. Quartz is platy and ribbon-textured, K-feldspar is perthitic, often with microcline twinning and signs of dynamic recrystallization. Plagioclase is albite to oligoclase, myrmekite has developed locally. The micas form a "mica-fish" texture. Biotite is Fe-rich, often replaced by chlorite. Muscovite is slightly phengitic; some $^{40}Ar/^{39}Ar$ spectra are discordant due to an Alpine overprint. Garnet is almandine and spessartine-rich, and it is partly replaced by biotite and chlorite. Accessory minerals are apatite, zircon and monazite. Cathodoluminescence study of zircons revealed that the cores are overgrown by magmatic rims; U-Pb dating of these zircons provided the lower intercept age of 406 ± 5 Ma recording magmatic zircon crystallization, whereas the upper intercept of 1980 ± 37 Ma age indicates an inherited material in the zircon (Poller *et al.*, 2000).

## 2.10 Field stop 10: Granitic rocks, Starý Smokovec, Hrebienok

**Locality:** Starý Smokovec, Hrebienok, High Tatra Mts.
**Geographical coordinates:** N 49°10.05′; E 20°13.10′
**Key words:** Tatra Mts., granitic rocks, pseudotachylite, rock-forming and accessory minerals, geochemistry, geochronological dating.
**Locality description:**
***Position:*** The High Tatra Mountains are the smallest high mountains, probably the smallest Alpine-type mountain in the world (Figs. 10.1–10.2). The Hrebienok near Starý Smokovec village where granite crops out is a turistic point accessible by a funicular train (Fig. 10.3). The granitic rocks belong to the Paleozoic basement of the Tatric Superunit of the Central Western Carpathians.

***Granitic rocks:*** Granite is medium- to coarse-grained with local phenocrysts of pinkish K-feldspar. Biotite and muscovite-biotite granodiorite to granite slightly porphyric: the "common Tatra type" is cropping out at the locality Hrebienok at the destination of the cogged-railway . Predominance of biotite granodiorite named "High Tatra type" (Kohút & Janák, 1994) to tonalite to muscovite-biotite granodiorite is typical for the eastern part of Tatra Mts. Single-crystal zircon age is 314 Ma but occurence of a diorite with ~340 Ma age is also known (Poller & Todt, 2000; Poller *et al.*, 2001). East from Hrebienok is the Gerlach peak – the highest summit in Slovakia – where occurences of phosphorus-enriched enclaves dated by zircon giving age of 345 ± 5 Ma (Gaweda, 2008) has been found. The mineral composition of granodiorite is plagioclase (~50 vol%), quartz (~30 vol%), K-feldspar

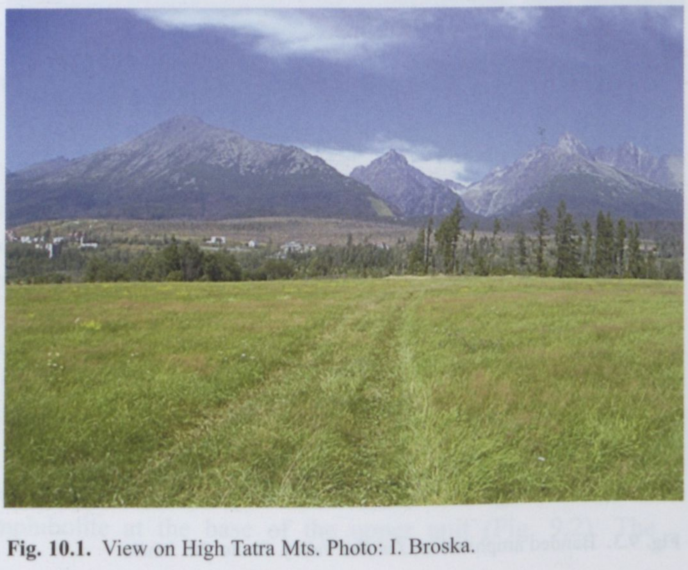

**Fig. 10.1.** View on High Tatra Mts. Photo: I. Broska.

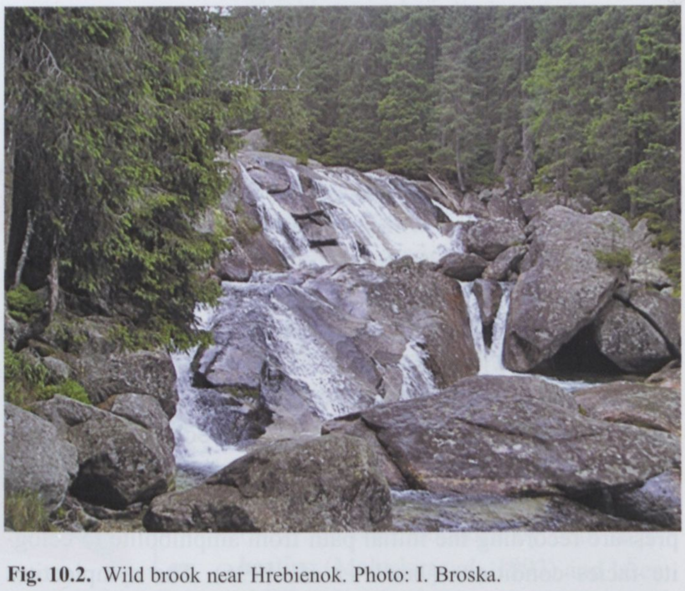

**Fig. 10.2.** Wild brook near Hrebienok. Photo: I. Broska.

**10.3.** Indoor of the Hrebienok funicular train. Photo: I. Broska.

(6 vol%), biotite (10 vol%) ± muscovite, accessory minerals comprise mainly apatite, zircon, monazite, magnetite and ilmenite. Plagioclase I with $An_{35-45}$ is enclosed in twinned phenocryst of plagioclase II of $An_{15-30}$. Albite commonly occurs in interstitial position between older plagioclase. Petrographically, the "common Tatra granite" represents a crustal anatectic rock with magmatic muscovite. The dominance of $Na_2O$ over $K_2O$ is typical. The Rb/Sr ratios are around 0.05–0.35 and initial strontium ratios are around $I_{Sr}$ = 0.705–0.706; these data indicate an inhomogeneous, weakly differentiated lower crustal source or possibly a mantle input. The Pensylvanian Variscan uplift at 312 ± 25 Ma was documented by $^{40}Ar/^{39}Ar$ dating of biotite from migmatitic garnet sillimanite gneiss in the Velická valley (Janák, 1994).

The Tatra granitic rocks form sheet-like intrusions (Kahan, 1969) and they are located in the hanging wall of the Variscan nappe system preserving the inverted metamorphic zonation (Janák, 1994). Metamorphic conditions in the wall rock of the granite show 700–750 °C temperature and 400–600 MPa pressure (Janák *et al.*, 1988; Janák, 1994), indicating syn-kinematic emplacement of the granitic pluton in middle crustal level during the Variscan uplift.

**Fig. 10.4.** Pseudotachylite veinlets in granodiorite. Batizovské Lake valley. Photo: I. Petrík.

North from the Hrebienok in the valley of the Batizovské Lake, pseudotachylite veinlets occur. They originated by frictional melting of the granite during ancient Miocene earthquakes when the Tatra Mts. have been uplifted (Fig. 10.4). The earthquakes were located in depth of 10–12 km. The pseudotachylite is a Fe-rich rock with hematite content up to 26 vol% (Petrík *et al.*, 2003).

## Day 4 (Thursday, 19 August 2010)

### 2.11. Field stop 11: Mineralization in basalts, Poprad, Kvetnica

**Locality:** Poprad, Kvetnica quarry
**Geographical coordinates:** N 49°01.51′; E 20°16.90′
**Key words:** Kozie Chrbty Mts., Permian basalt, rock-forming minerals, hydrothermal minerals, Cu mineralization

**Locality description:**

***Position:*** The active quarry is situated on N slope of the Kozie Chrbty Mts., ~7 km S of Poprad town, in an W–E trending belt of Permian metabasalt of the Malužiná Formation, the Ipoltica Group, a part of the Hronic Superunit of the Central Western Carpathians.

***Volcanic rocks:*** Basalt, locally andesite, belong to the 2nd eruption phase of the volcanic activity within the Malužiná Formation, a 400 to 800 m thick volcano-sedimentary complex with lava flows, horizons of volcano-clastic and sedimentary rocks. The thickness of lava flows is from 150 to 300 m. Lava breccia and hyaloclastite occur at the bottom of lava flows which locally show 20–30 cm thick contact thermal aureole along the contact with adjacent clastic sedimentary rocks. Porous and amygdaloidal varietes of basalt are characteristic in the marginal parts of the lava flows, whereas massive fine-crystalline, locally porphyric rock form their central parts. The basalt shows mostly tholeiitic character and is related to the post-Hercynian continental rift-related volcanism (Vozár, 1997). Late Permian age is assumed for the 2nd eruption phase of volcanic activity within the Malužiná Formation on the basis of geological position and paleontological records in the adjacent sedimentary rocks. The volcanic rocks were overprinted by very-low-grade metamorphism (prehnite–pumpellyite facies) and thrust nappe movement during the Alpine orogenesis.

***Rock-forming and post-magmatic minerals:*** primary composition of plagioclase phenocrysts is labradorite (~60 mol% of anorthite); however they are commonly albitized or partly replaced by fine-crystalline muscovite (sericite), chlorite and calcite. Green epidote crystals, clinochlore and hematite (variety specularite) form fracture fillings in the volcanic rocks. Analcime (Dyda, 2009), calcite, quartz (locally smoky quartz and amethyst), chalcedony, opal and agate (Figs. 11.1–11.2) form infillings in amygdales. Rare pumpellyite forms thin veinlets and accumulations of bluish-green fibrous radial aggregates in association with epidote, calcite, quartz and Cu sulphide minerals (Vrána, 1966).

**Fig. 11.1.** Agate, Kvetnica quarry. Specimen size 10 cm. Photo: P. Uher.

Fig. 11.2. Agate, Kvetnica quarry. Specimen size 12 cm. Photo: P. Uher.

***Hydrothermal Cu-mineralization:*** The hydrothermal mineralization form impregnations, veins and veinlets in the basaltic-andesitic volcanic rocks. Primary hydrothermal minerals are chalcopyrite, chalcocite I, bornite, tetrahedrite, tennantite, gersdorffite, pyrite, marcasite, sphalerite, galena and barite; covellite, chalcocite II, azurite, malachite, chrysocolla and goethite (limonite) belong to the secondary paragenesis (Ferenc & Rojkovič, 2001).

## 2.12 Field stop 12: Dobšiná Ice Cave

**Locality:** Dobšiná, Dobšiná Ice Cave (Dobšinská l'adová jaskyňa)
**Geographical coordinates:** N 48°52.11′; E 20°18.10′
**Key words:** Slovak Paradise National Park, karst, ice cave

**Locality description:**
***Position:*** The Dobšiná Ice Cave is located on the SW edge of the Slovak Paradise National Park, in the Spiš-Gemer karst, 6 km NW from Dobšiná town. Cave entrance is situated on the northern slope of the Duča Hill at the elevation of 969 m, 130 m above the bottom of the Hnilec Valley. The cave is situated in Middle Triassic limestone of the Stratená Group, the Gemeric Superunit, Central Western Carpathians.

***Natural settings of the cave:*** The Dobšiná Ice Cave is a part of the Stratená Cave System. It has been formed along the tectonic faults and interbed surfaces. The cave reaches the length of 1483 m and vertical span of 112 m (Fig. 12.1). The main part of the cave is represented by a giant cavity descending from the entrance to the depth of 70 m, which was formed by breakdown of rock columns between the passages formed by palaeoflow of Hnilec river in several levels. At present, most of its volume is filled with ice, sometimes up to the ceiling, by which it is divided into individual parts, *e.g.* Great and Small Hall, Ruffiny's Corridor, Ground Floor and Collapsed Dome (Fig. 12.2). Original oval shapes of river flow-paths are almost entirely destructed by collapses and frost weathering. The upper, non-glaciated parts of the cave contain mostly horizontal passages and halls with typical oval shapes and ceiling channels. There are also some forms of flowstone fills in the non-glaciated parts of the cave (stalagmites, stalactites, flowstone crusts, layers of moonmilk).

Conditions for glaciation arose probably in the middle Quaternary period after the breakdown of ceilings between the Dobšiná Ice Cave and Stratenská Cave. Consequently, the cave obtained sack-like character with stagnation of cold air that penetrated into the cave through the upper opening formed by collapse of the ceiling part (present entrance to cave). Freezing the percolating rainfall waters caused glaciation in the underground space. The beginnings of ice formation go back to the Riss ice age (~300,000 to 140,000 years ago), or until the end of the Mindel ice age. Ice fill occurs in the form of floor ice, icefalls, ice stalagmites and columns. The glaciated surface is 9772 m$^2$, and ice volume reaches 110,000 m$^3$. The largest thickness of ice is in the Great Hall with 26.5 m. The floor ice is characterized by its stratification. The decrease of ice takes place by melting along the contact with the bedrock. Continuous replacement of the underground glacier supposedly takes around 1700 up to 2000 years. The ice is slowly moving from the entrance, Small and Great Hall towards the Ground Floor and Ruffiny's Corridor (2 to 4 cm per year). The Dobšiná Ice Cave belongs among the most significant ice caves in the world, which is accentuated by its location outside the Alpine high-mountain region (underground ice is at the elevation of 920 to 950 m above sea level). Average annual temperature of air in the glaciated Great Hall reaches –0,4 to –1,0 °C (in February –2,7 to –3,9 °C, in

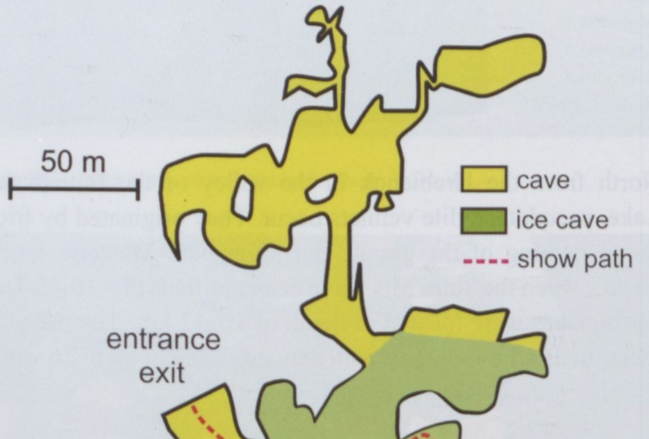


Fig. 12.1. Schematic map of the Dobšiná Ice Cave (courtesy of M. Orvošová, Slovak Museum of Nature Protection and Speleology, Liptovský Mikuláš).

**Fig. 12.2.** a) Detail from the Dobšiná Ice Cave. Photo: P. Gažík; b) Ice formations from the Dobšiná Ice Cave. Photo: J. Zalinka (by courtesy of M. Orvošová).

August around +0,2 °C). The temperature in the bottom parts of the cave remains under the freezing point all the year round. Relative air humidity in non-glaciated parts is mostly 75 to 90%, sometimes over 90%. Air temperature in the non-glaciated parts of the cave fluctuates between +0.8 and +3.5 °C, and the relative humidity is between 85 and 98%. The cave is under static-dynamic conditions and different winter and summer regime of airflow circulation.

***History:*** Opening to the cave called "the ice hole" was known since long time ago. However, it was only J. Ruffinyi mining engineer accompanied by G. Lang, A. Méga and F. Fehér who descended underground in 1870. Thanks to the town of Dobšiná, the cave was opened for the public as early as 1871. The cave belongs among the first electrically illuminated caves in the world: experiments with electric lighting began in 1881 and regular electric lighting was introduced in 1887. A concert was held in the Great Hall in 1890 to the tribute of Karl Ludwig von Habsburg. It was known also by summer skating, which took place for the first time in 1893. A skating for public was permitted all year round before 1946.

***Visiting route:*** Duration of visit is ~30 min., length of the visiting path is 515 m including a descent of 43 m.

## 2.13 Field stop 13: Mineralization in serpentinites, Dobšiná

**Locality:** Dobšiná, serpentinite quarry
**Geographical coordinates:** N 48°49.43´; E 20°21.98´
**Key words:** serpentinite, peridotite, chrysotile, Cr and Ni mineralization, magnesiochromite, chromian andradite, awaruite, heazlewoodite, pentlandite

**Locality description:**

***Position:*** The large abandoned quarry is located in the northern part of the small town of Dobšiná. Subhorizontal lense-shaped serpentinite body (Fig. 13.1) attains dimension of ~70 to 200-500 m with maximal thickness of 45 m; the serpentinite is situated within Lower Triassic shale and it is in tectonic contact with underlying Pennsylvanian (Upper Carboniferous) schist (Hovorka, 1985). The serpentinite represents an isolated tectonic fragment of the Meliatic Superunit, a remnant of a Triassic oceanic suture (Hovorka, 1985; Plašienka *et al.*, 1997).

***Serpentinite mineralization:*** The rock represents lizardite–chrysotile serpentinite, a highly serpentinized harzburgite peridotite. The serpentinite contains ~38–40 wt% $SiO_2$, 1–2 wt%

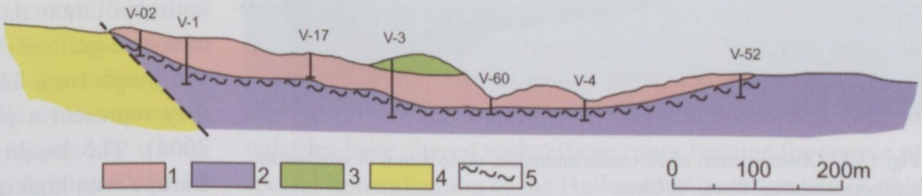


**Fig. 13.1.** Geological cross-section of the Dobšiná serpentinite body (Zlocha & Hovorka, 1971, adapted). 1 – serpentinites; 2 – Pennsylvanian schists; 3 – Mesozoic limestones; 4 – Paleozoic metamorphic rocks; 5 – tectonic boundary.

$Al_2O_3$, 4–10 wt% $Fe_2O_3$ + FeO, 30–40 wt% MgO, 0.1–9 wt% CaO, <0.1 wt% $Na_2O$ and $K_2O$, 13 wt% $H_2O$ + $CO_2$, 1400 g/t Ni, 3100 g/t Cr (Hovorka, 1985), 15 ppb Pt, 84 ppb Pd, 5 ppb Rh, 4 ppb Ru and 10 ppb Au (Hovorka *et al.*, 1980). Primary minerals of peridote comprise olivine, orthopyroxene, clinopyroxene, Cr-spinel and sulphide minerals. Sporadic relicts of olivine contain 90–91 mol% of forsterite, and orthopyroxene shows enstatite composition ($En_{88-89}Fs_{09}Wo_{01-03}$), and clinopyroxene is characterised by diopside ($En_{49-50}Fs_{04}Wo_{46-47}$) composition (Hovorka, 1985). Chromium-rich spinel, magnesiochromite with 52 wt% $Cr_2O_3$ (Mg/(Mg + Fe) = 0.51, Cr/(Cr + Al + $Fe^{3+}$) = 0.70 forms brown-red grains, usually up to 2 mm large in the groundmass, locally also accumulations with olivine, several kg in weight, with ~40 vol% of the Cr-rich spinel (Rojkovič *et al.*, 1978). Awaruite ($Ni_{2-3}Fe$) forms rare 0.1–0.2 mm large grains and acumulations in the serpentinite grounmass in association with heazlewoodite ($Ni_3S_2$), millerite (NiS) and pentlandite (Kantor, 1955).

**Fig. 13.2.** Chrysotile veinlets in serpentinite, up to 1-2 mm in thickness, Dobšiná. Photo: P. Uher.

**Fig. 13.3.** Green crystals of chromian andradite, up to 4 mm in size, on serpentinite, Dobšiná. Photo: P. Uher.

Serpentine-group minerals, garnet (chromian andradite) and magnetite are the products of serpentinization and younger Alpine metamorphic overprint of primary peridotite. Lizardite forms the main part of the serpentinite groundmass, whereas chrysotile occurs as common veins and fracture fillings of fibrous yellow-green crystals with up to 3-cm lenght (Fig. 13.2). Chromian andradite forms up to 3 mm large yellow-green to emerald green crystals, disseminated in the groundmass or as several cm large aggregates in the serpentinite fissures or in serpentinite veinlets (Fig. 13.3). Andradite contains up to 8 wt% $Cr_2O_3$ and 0.1–0.3 wt% NiO, 78–97 mol% andradite, 2–20 mol% uvarovite, 0–5 mol% grossular, 1–6 mol% pyrope; the crystals shows compositional zoning with decreasing of Cr (uvarovite end-member) and increasing of Fe (andradite end-member) contents from the centre to the rim (Fediuková *et al.*, 1976).

Hydrothermal galena in association with secondary anglesite, cerussite, georgiadesite $Pb_4[(OH)Cl_4(AsO_4)]$ and mimetite occurs in the marginal parts of the Dobšiná serpentinite body (Ďuďa & Peterec, 1992). Moreover, agate-like material with white and red concentric texture forms irregular vugs and veinlets in the serpentinite.

## 2.14 Field stop 14: Sn-bearing granites and greisens, Gemerská Poloma, Dlhá dolina valley (Dlhá valley)

**Locality:** Gemerská Poloma, Dlhá dolina valley (Dlhá valley)
**Geographical coordinates:** N 48°46.11´; E 20°31.91´
**Key words:** Slovak Ore Mts., specialized tin-bearing S-type granite, greisen, cassiterite, wolframite, Nb-Ta-W minerals, Li mica, topaz, tourmaline

**Locality description:**
***Position:*** At the termination of the Dlhá dolina ('long valley' in Slovakian), N of Gemerská Poloma village, a greisenised granite cliff with visible cassiterite is exposed. There is a prospection adit which has been opened in order to reach a talc deposit occurring along the contact of the specialised S-type granite and magnesite (Figs. 14.1–14.2). The greisenised granite and the adjacent Lower Paleozoic phyllite belong to the Gemeric Superunit of the Central Western Carpathians.

***Specialized S-type granites in the Gemeric Unit***

Granite in Gemeric Superunit crops out in small bodies, which have been emplaced into intensively folded Lower Palaeozoic volcano-sedimentary complexes of the Gemeric Superunit. This superunit consists mainly of phyllite and pyroclastite with rhyolitic to dacitic compositions as well as locally lenses of coarse-grained carbonate rocks (dolomite, ankerite, siderite and magnesite). The magnesite is intensively steatitized and they represent a potential source for talc (Radvanec *et al.*, 2004). The locality belongs to the largest talc deposits in Europe with high quality raw material.

**Fig. 14.1.** Entrance of the exploration adit in Dlhá dolina valley near Gemerská Poloma. Photo: P. Uher.


**Fig. 14.2.** Cassiterite aggregate (dark brown) in quartz, Dlhá dolina valley. Photo: P. Uher.

The Gemeric Unit underwent greenschist facies metamorphism at around 300-350 °C temperature and 0.5–0.7 GPa pressure during the Alpine orogeny (Krist *et al.*, 1992; Faryad & Dianiška, 1999). The chemical composition of the Spiš-Gemer granite is generally characterized by high $SiO_2$ (up to 77 wt%), low MgO and CaO, high alkali elements, especially $K_2O$ (around 5 wt% in average) contents and enriched concentrations of volatile elements (B, F). Because of the occurrences of Sn, Nb, Ta, W mineralization in their most evolved segments (Grecula, 1995; Malachovský *et al.*, 2000; Uher *et al.*, 2001), parts of the granite can be classified as specialized S-type granite (Uher & Broska, 1996).

The specialized S-type granite in the Gemeric Superunit may have resulted from melting triggered by increased heat flow from the mantle below the continental crust during the post-collisional extension after the main Hercynian orogeny. Permian age of the Spiš-Gemer granites is reported by whole-rock Rb-Sr analyses (Cambel *et al.*, 1990), chemical U-Th-Pb monazite dating (276±13 Ma; Finger & Broska, 1999), and U-Pb single zircon dating (~250 Ma; Poller *et al.*, 2002). The age is also indicated by molybdenite Re-Os dating of the ore mineralization occurring in the exocontact of granite (262 ± 1 Ma; Kohút *et al.*, 2004; Kohút & Stein, 2005).

***Dlhá dolina valley granite pluton***

The Dlhá dolina valley pluton is composed from two parts: the deeper complex of barren two-mica monzogranite and bitotite porphyry and the upper complex of fractionated rare metal Li-F granites. There are bitotite granite porphyry with tourmaline and two-mica medium-grained porphyritic granite with tourmaline in lower part. The upper part consists of protolithionite granite with tourmaline and topaz–zinnwaldite granite (Dianiška *et al.*, 2002). Li-F granites are formed in the apical parts due to magmatic fractionation and hydrothermal (metasomatic) overprint (Fig. 14.3).

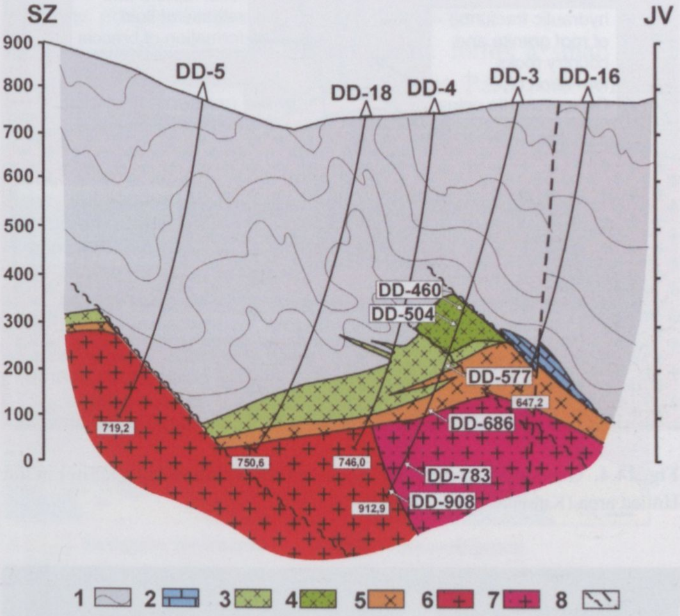


**Fig. 14.3.** Cross-sections of the Dlhá dolina valley Sn deposit (Dianiška *et al.*, 2002). 1 – metasediments of the Gelnica group, 2 – coarse-grained dolomites, 3 – topaz–zinnwaldite–albite granite, 4 – albitite with fissure greisens, 5 – protolithionite granite, 6 – fine-grained biotite granite porphyry, 7 – medium-grained two-mica porphyritic granite, 8 – faults, 9 – boreholes, 10 – position of the samples in the borehole DD-3.

Closed greisen formation in the Hnilec region (N from Dlhá dolina valley) has been also interpreted as a process connected with the magmatic fluid emanation in the Hnilec granite cupola on Medvedí Potok locality (Fig. 14.4). An emanation spot was room for high volatile flux formed beneath fine-grained granite carapace or between fine and coarse-grained granites in the overpressurring regime. Where vapour pressure of the exsolving fluid exceeded lithostatic pressure it caused the rupture of the overlying crystalline rocks and flux of volatiles have altered rocks: these zones became the source of special mineralization of the Hnilec and Gemer granite (Kubiš

& Broska, 2005). Similar processes operated in evolved granite bodies, which have been intensively studied by drill core exploration program for tin during 1980s in the Dlhá dolina valley. The granite from the Dlhá dolina valley is known by occurrences of cassiterite-bearing veins and greisen formation located as the cliff in the valley termination.

Cassiterite forms visible, up to 5-cm large dark brown aggregates of tiny crystals in greisen and related quartz veinlets (Fig. 14.5). Cassiterite is relatively homogeneous, but it contains up to 5 wt% $Ta_2O_5$ + $Nb_2O_5$. Several exploration boreholes also revealed rare-element Li-Sn-W-Nb-Ta mineralization in relation to topaz–albite leucogranite with polylithionite–protolithionite mica and accessory cassiterite, ferrocolumbite to manganocolumbite, Nb,Ta-bearing rutile, ixiolite, and Nb-rich wolframite. Complex Fe-Mn-Nb-Ta-W oxide phases (including qitianlingite?) were also detected (Malachovský *et al.*, 2000; Uher *et al.*, 2001). Ferrocolumbite to manganocolumbite associate with cassiterite, W-rich phases, mica and quartz, locally it shows distinct oscillatory zoning (Fig. 14.6). Relatively large Mn/Fe but restricted Ta/Nb compositional variations are characteristic for the Dlhá dolina valley and the Hnilec and Poproč granite: Mn/(Mn + Fe) = 0.05 to 0.90, Ta/(Ta + Nb) = 0.01 to 0.45. Elevated W and Ti contents are characteristic to the ferrocolumbite-ferrotantalite (max. 14 wt% $WO_3$ and 7 wt% $TiO_2$). Generally, increasing of Ta and W from center to rim of the columbite crystals was

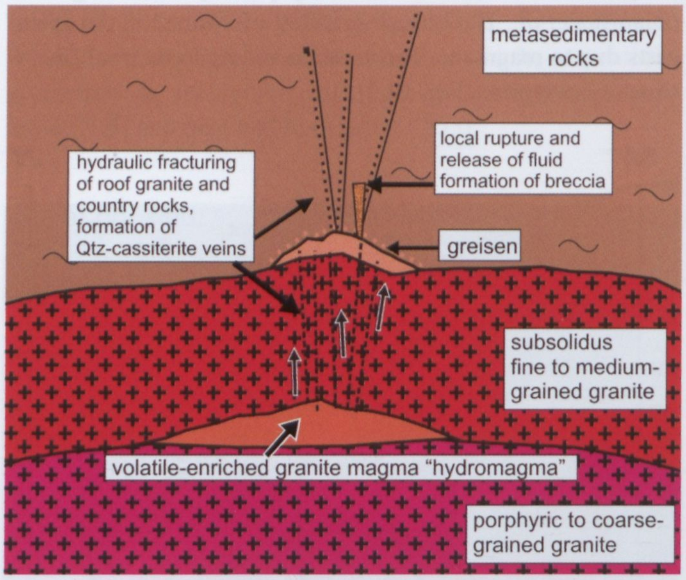


**Fig. 14.4.** General features of roof-zone granite evolution (apogranite) in the Hnilec area (Kubiš & Broska, 2005).

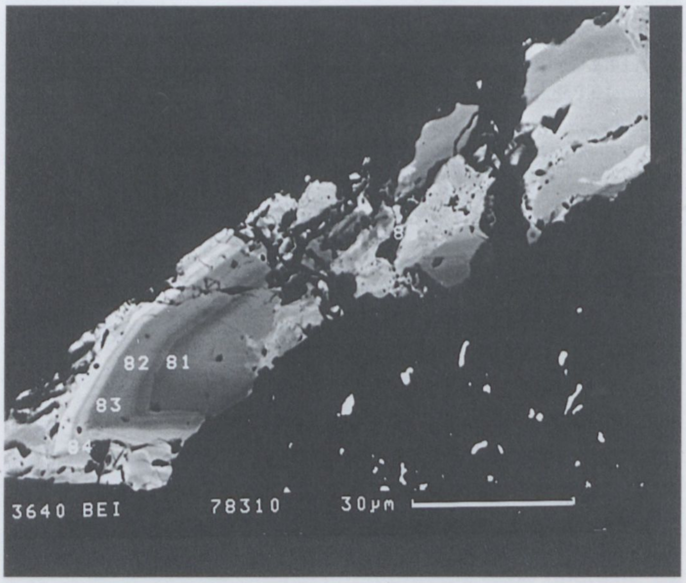


**Fig. 14.6.** Oscillation zoning of ferrocolumbite to manganocolumbite, Dlhá dolina valley. BSE image, photo: P. Sulovský.


**Fig. 14.5.** Cassiterite (cs) in association with columbite (ko), Dlhá dolina valley. BSE image, photo: P. Sulovský.

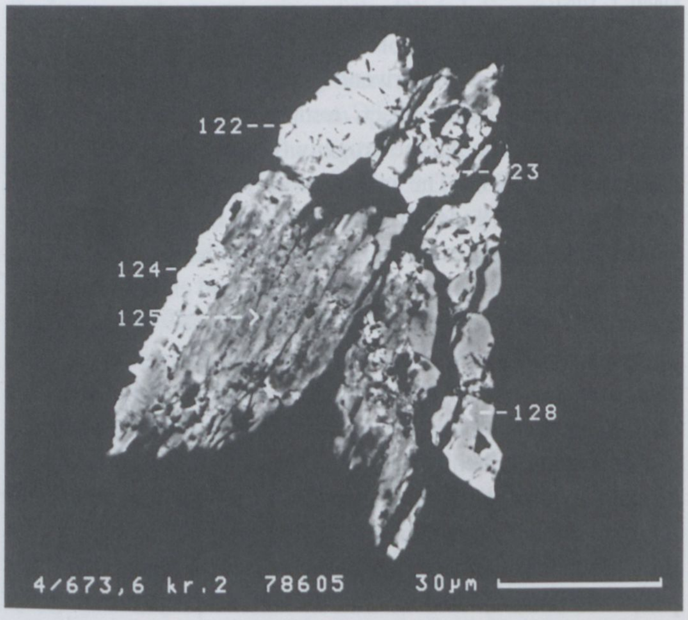


**Fig. 14.7.** Intergrowths of qitianlingite? (grey) and Nb-rich ferberite (white), Dlhá dolina valley. BSE image, photo: P. Sulovský.

detected. The highest Ta and Mn contents in the columbite occurs mainly in the most fractionated rare-element granite in the Dlhá dolina valley, in comparison to the less fractionated Hnilec and Poproč granite. Nb,Ta-bearing rutile (ilmenorutile to strüverite) contains max. 5 wt% $WO_3$, 15 wt% $Nb_2O_5$ and 27 wt% $Ta_2O_5$; Mn/(Mn + Ta) = 0.00 to 0.18 and Ta/(Ta + Nb) = 0.06 to 0.76. The highest W, Nb and Ta concentrations are in the most fractionated granite again. W-rich ixiolite and the Nb,Ta-rich ferberite are the most widespread W-bearing minerals. In addition, a rare phase with stoichiometry close to qitianlingite $(Fe,Mn)_2(Nb,Ta)_2WO_{10}$ was identified in up to 20 µm large anhedral intergrowths with ferberite or W-rich ixiolite (Fig. 14.7). The qitianlingite-like phase contains 32 to 39 wt% $WO_3$, Mn/(Mn + Fe) = 0.26-0.39 and Ta/(Ta + Nb) = 0.05-0.35.

Tourmaline-bearing granite forms the underlying main facies of the topaz–albite and greisenised granite in boreholes at the Dlhá dolina valley (Fig. 14.8). Primary magmatic schorl shows high Fe content: the Fe/(Fe + Mg) ratio is 0.9–1 and it increases with the degree of magmatic fractionaction. Similarly, the F content or the F/(F + OH) ratio generally increase with the magmatic fractionation of the Spiš-Gemer granite; the F/(F + OH) is equal 0.3 to 0.6 in the less fractionated granite members, whereas the ratio attains 0.5 to 0.9 in the most fractionated Li mica- and topaz-bearing albite granite with presence of the Nb-Ta-W minerals. Older primary magmatic schorl shows lower X-vacancies and higher Na contents [(X-vac./(X-vac. + Na) = 0.1–0.3], whereas younger, probably early post-magmatic schorl to foitite displays a relatively large vacancy in the *X*-site, up to 0.68 *apfu* (Broska *et al.*, 1998, 1999). Ti and Ca contents in the magmatic tourmalines are generally low to moderate (up to 0.1 *apfu*). Moreover, the youngest metamorphic, probably Alpine tourmaline replace the magmatic to post-magmatic schorl to foitite; it shows mainly dravitic composition with Fe/(Fe + Mg) = 0.1 to 0.6 (Fig. 14.8).

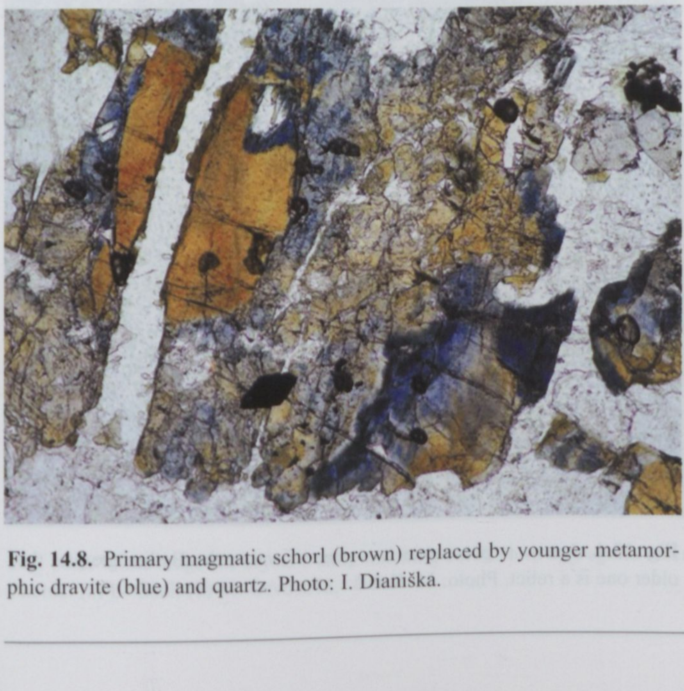

**Fig. 14.8.** Primary magmatic schorl (brown) replaced by younger metamorphic dravite (blue) and quartz. Photo: I. Dianiška.

# Day 5 (Friday, 20 August 2010)

## 2.15 Field stop 15: Tourmaline-bearing granites, Betliar

**Locality:** Betliar

**Geographical coordinates:** N 48°43.70′; E 20°31.95′

**Key words:** Slovak Ore Mts., specialised S-type granite, porphyric granite, fine-grained leucogranite, rock-forming and accessory minerals, tourmaline

**Locality description:**

***Position:*** Cliffs of coarse-grained granite and granitporphyre occur in a game-preserve area. The cliffs are several meter high and expose granite intrusions into low metamorphic metapelite of Missisipian age. Several cm large tourmaline nodules and long tourmaline veins are commonly observable on these cliffs. Moreover, fine-grained leucogranite in contact with the porphyric granite also occurs here.

***The Betliar granite body:*** Granite forms a small body emplaced into intensively folded Lower Paleozoic volcano-sedimentary complexes of the Gemeric Superunit (Fig. 15.1).

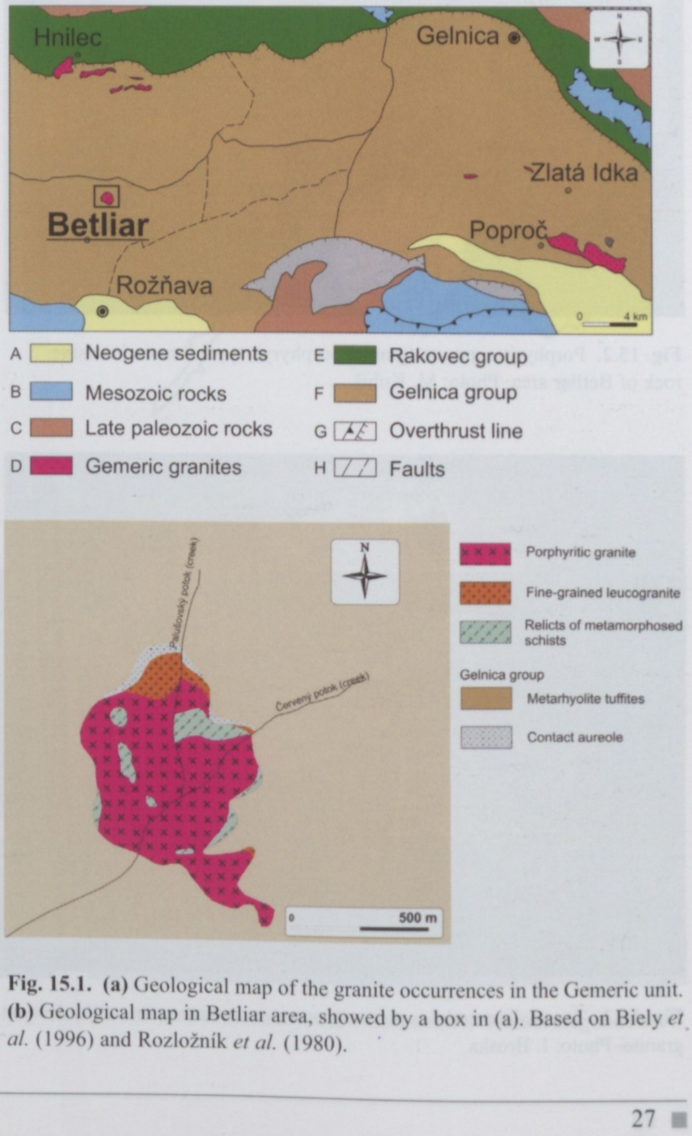


**Fig. 15.1.** **(a)** Geological map of the granite occurrences in the Gemeric unit. **(b)** Geological map in Betliar area, showed by a box in (a). Based on Biely *et al.* (1996) and Rozložník *et al.* (1980).

The Betliar granite body consists of two main lithological types: tourmaline-bearing coarse-grained porphyric granite (Fig. 15.2) and highly evolved fine-grained granite partly with greisenised parts. The Betliar body is characterised by the occurrence of the tourmaline nodules in granite (Fig. 15.3).

Generally, the porphyritic granite is peraluminous (A/CNK = 1.2 to 1.6), with high $SiO_2$ content (73 to 75 wt%), relatively high alkalies, especially $K_2O$ (3 to 5 wt%) and Rb (300–420 g/t), but relatively low to medium content of MgO (0.3 to 0.9 wt%), CaO (0.26 to 0.42 wt%), FeO (1.25 to 1.75 wt%), $P_2O_5$ (~0.15 wt%), Sr (13 to 33 g/t), Ba (104 to 246 g/t) and Nb (10-12 g/t). The rock is also enriched in B (~375 g/t), and it shows pronounced negative Eu anomaly (Eu/Eu* = 0.22 to 0.31) and low $La_N/Yb_N$ (2.2 to 3.8).

Fig. 15.2. Porphyritic granite (granite porphyry), typical main intrusive rock of Betliar area. Photo: M. Kubiš.

The fine-grained granite occurs in the northern part of the Betliar granite body. It is strongly peraluminous (A/CNK = 1.4 to 2.4) and distinctly enriched in P (0.37 to 0.47 wt% $P_2O_5$) and Rb (550 to 700 g/t). A higher degree of fractionation is documented also by increased concentrations of rare metals: Nb (47 to 73 g/t), Ta (14.3 to 18.2 g/t) and W (21 to 38 g/t). ***Rock-forming minerals:*** All two rock types contain relatively pure end-members of alkali feldspar: albite with <0.5% Ab and K-feldspar (Kfs) with a maximum of 0.1% Ab and <0.1% An. The $P_2O_5$ content in K-feldspar of the porphyric granite attains 0.11 to 0.25 wt% and 0.02 and 0.23 wt% in albite. On the other hand, the $P_2O_5$ content of albite in the fine-grained granite is very low (0.01-0.09 wt%).

Annite shows two different generations. The first generation is formed by xenomorphic lamellae with inclusions of zircon and apatites. There is often chloritisation developed. The younger generation is developed as hypiodiomorphic grains with common inclusions of ilmenite, rutile and titanite (Fig. 15.4). Annite from Betliar granite porhyry show high 0.79–0.81 Fe/(Fe + Mg) ratio and $^{IV}Al$ = 0.98–1.26, Ti is in the range 0.08–0,11. Relatively low F content (0.01-0.28 *apfu*) is typical. Dioctahedral mica in both granite types corresponds to ferro-aluminoceladonite and aluminoceladonite. The white mica contains relatively high concentrations of heterogeneously distributed Fe (1.7–6.0 wt% $FeO_{total}$) (Kubiš, 2004).

***Accessory minerals:*** Tourmaline is a widespread accessory mineral in the porphyric granite, and forms two genetic types. The first type is scattered in the host granite and it is represented by a primary magmatic schorl with 0.7–1.0 ratio of Fe/(Fe + Mg) and lower X-site vacancy (X□ = 0.1–0.45 *apfu*). The second type, a late-magmatic or metamorphic schorl/dravite with 0.45–0.65 Fe/(Fe + Mg) ratio, forms mobilised veins and clusters in the granite as a result of mixing of juvenile and country-rock fluids. Tourmaline clusters or nodules are typically spherical bodies from 1 to 5 cm in

Fig. 15.3. Tourmaline nodules are very common in some part of the Betliar granite. Photo: I. Broska.

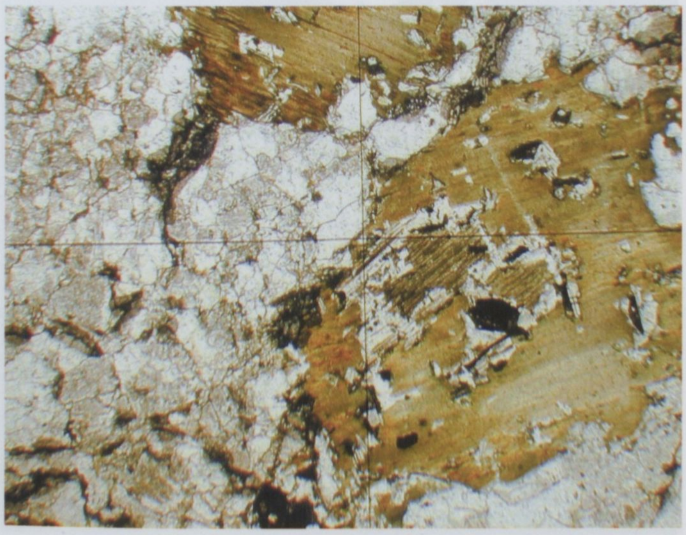

Fig. 15.4. Annite is present in two generations in the Betliar granite, the older one is a relict. Photo: M. Kubiš.

diameter, consist of tourmaline and quartz (± feldspar) core surrounded by quartz + feldspar halo. Decompression along path during approach to and at the shallow emplacement level triggered the exsolution of fluid phase from melt and its mixing with fluids from the roof part leads to a rise of volatile concentration in melt. Exsolution of volatiles from a convecting magma form individual vapour bubbles in the magma which coalesce at the top of the magma body and tend to accrete into a sphere to decrease surface tension. Tourmaline nodules in Betliar are the analogue of the similar process described from the Moslavačka Gora Mts., Croatia (Balen & Broska, 2010).

Apatite is present in two types (generations). The first (primary) type is represented by large crystals (~150 µm), which are enriched in Mn and Fe (3–4 wt% MnO and 0.2–0.9 wt% FeO), whereas the secondary apatite is distributed within alkali feldspars as a product of leaching of the berlinite molecule (Fig. 15.5). They form very small crystals (~3 µm) with low content of Mn and Fe and usually within plagioclase. Monazite-(Ce) with 3.3-9.5 wt% $ThO_2$ and 0.1-0.25 wt% $UO_2$ is the main LREE host in the porphyric granite. Cheralite with 27–33 wt% $ThO_2$, 1–4 wt% $UO_2$ has also been found in the fine-grained granite in association with wolframite. Xenotime-(Y) + zircon paragenesis is typical for the porphyric granite. The zonation observed in xenotime-(Y) is mainly due to the variation of U concentrations.

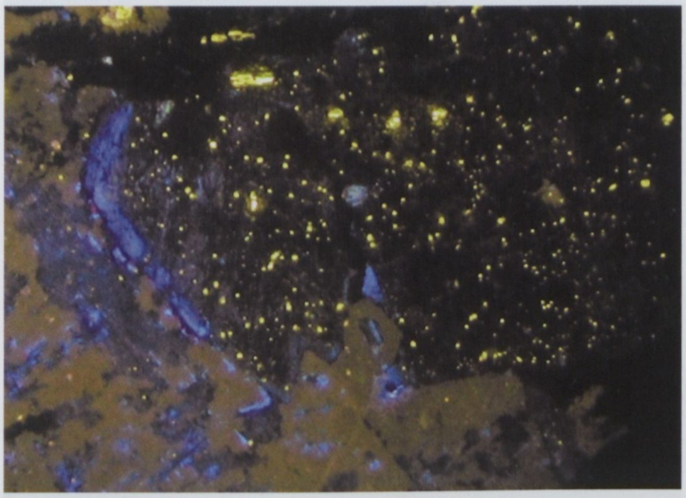

**Fig. 15.5.** Cathodoluminiscence image of feldspars in granite from Betliar. Yellow spots are apatite grains, newly formed from the breakdown of alkali feldspars. Photo: J. Leichmann.

## 2.16 Field stop 16: Ochtiná aragonite cave

**Locality:** Ochtiná aragonite cave (Ochtinská aragonitová jaskyňa)

**Geographical coordinates:** N 48°39.89′; E 20°18.64′

**Key words:** Slovak Ore Mts., metacarbonate, aragonite cave

**Locality description:**

***Position:*** The Ochtiná aragonite cave (Ochtinská aragonitová jaskyňa, Fig. 16.1) is situated in the Hrádok Hill (809 m asl), ~6 km NW of the town of Jelšava in the Slovak Ore Mountains. Entrance adit leads to the cave at the elevation of

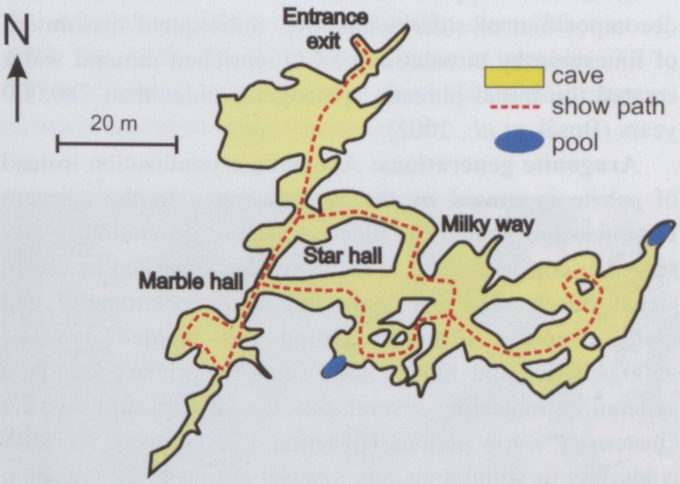


**Fig. 16.1.** Schematic map of the Ochtiná aragonite cave (courtesy of M. Orvošová, Slovak Museum of Nature Protection and Speleology, Liptovský Mikuláš, Liptovský Mikuláš).

**Fig. 16.2.** White aragonite crystals and branching coralliform aggregates resembling "iron flower" in Devonian crystalline limestones, Ochtiná aragonite cave. Photos: (a) L. Gaál, (b) M. Orvošová.

642 m. Although the cave is 300 m long only, it is famous for its unique aragonite crystal decoration (Figs. 16.2a–b) and it is a locality of the UNESCO World Heritage List since 1995. The cave was discovered in 1954, and opened to the public in 1972. The artificial tunnel into the cave is 144 m long and overcomes the vertical distance of 19 metres with 104 steps. Cave visit lasts 30 minutes. Air temperature in the cave is between 7.2 and 7.8 °C, the relative humidity attains 92 to 97%. The cave microclimate is stabilised by ochres that contain 47–56 wt% $H_2O$ and they are able to absorb or release water vapour. The host Devonian limestone belongs to the Gelnica Group of the Gemeric Superunit.

***Origin of cave:*** The Lower Devonian crystallic limestone of the Ochtiná cryptokarst occurs in isolated lenses within adjacent phyllite. During the Upper Cretaceous, part of the limestone was metasomatically transformed into ankerites and siderites by hydrothermal fluids. Oxygen-enriched meteoric water seeping along the faults caused siderite/ankerite weathering and their transformation to goethite (limonite) ochres that were later removed by mechanical erosion. Corrosion was enhanced by weathering of hydrothermal pyrite and carbon dioxide released from decomposition of siderite/ankerite. Subsequent dissolution of limestone by circulation of $CO_2$-enriched mineral water created the initial phreatic speleogens, older than 780,000 years (Bosák *et al.*, 2002).

**Aragonite generations:** Aragonite crystallization instead of calcite is caused by the Sr enrichment in the adjacent Devonian limestone. The oldest aragonite generation is preserved as corroded relics in ceiling niches truncated by corrosional bevels. Thermal ionisation mass spectrometry and alpha counting U series dating has yielded ages of ~500–450,000 and 138–121,000 years for primary aragonite generation, indicating several episodes of deposition during Quaternary warm periods (Elsterian 1/2, Eemian). Acicular colourless to white aragonite crystals are up to 12 cm long, locally they are transformed into calcite. Water levels in the cave have fluctuated many times during its history: the cave was filled up by water during wet periods and then slowly drained. Mn-rich loams with Ni-bearing asbolane and birnessite were formed by microbial precipitation in the ponds remaining after the floods. Allophane was produced in the acidic environment of sulphide weathering. La-Nd-bearing phosphate and REE-rich Mn oxide minerals precipitated on geochemical barriers in the asbolane layers.

Ochres containing about 50 wt% of water influenced the cave microclimate and the precipitation of secondary aragonite. Spiral and acicular forms of aragonite representing a second generation began to be deposited in Late Glacial times (~14,000 years). The youngest aragonite frostwork continues to be deposited today. Both of the younger generations have similar isotopic compositions, indicating that they precipitated under conditions very similar or identical to those found at present in the cave (Bosák *et al.*, 2002).

## 2.17 Field stop 17: Mineralization in alkali basalts, Šomoška/Somoskő castle hill

**Locality:** Šomoška/Somoskő, castle hill
**Geographical coordinates:** N 48°10.43′; E 19°51.65′
**Key words:** Cerová Highland, alkali basalt, columnar basalt jointing, stone organs, rock-forming minerals, syenite and anorthosite xenoliths, sapphire

**Locality description:**

***Position:*** The Šomoška/Somoskő castle hill is situated in the Cerová Highland, an area of the youngest Tertiary–Quarternary alkali basalt volcanic activity, along the Slovak–Hungarian boundary, 7 km NNE of the town of Salgótarján in Hungary. The volcanic rocks of the Cerová Basalt Formation form a beautiful country scenery including remnants of diatreme fillings, lava necks, dykes and flows with characteristic columnar jointing ("stone organs"), ring maar structures, agglomerates and lapilli tuff accumulations. The medieval Šomoška/Somoskő castle (13th to 17th century) was built from the local basaltic columns (Fig. 17.1).

**Fig. 17.1.** Ruins of medieval Šomoška/Somoskő castle; the walls were built from basalt columns. Photo: P. Uher.

**Alkali basalts:** The Šomoška/Somoskő castle hill represents an example of a small volcanic chimney with transition to lava flow. The basaltic lava extruded on sandstone of the Fiľakovo and Bukovina Formations (Lower Miocene, Eggenburgian). Tuff with deformed basalt fragments and chimney volcanic breccia form the external parts, whereas massive basalt occupies the central part of the volcanic structure. Columnar jointing of the basalt (stone organs) is developed along the contacts with tuffs and breccias or adjacent sanstones. Regular pentagonal to hexagonal columns are usually 15 to 25 cm thick with subhorizontal, fan-like to subvertical orientation (Figs. 17.2–17.3). Generally, the columnar jointing of the volcanic rocks is the result of their contraction during cooling.

**Fig. 17.2.** Columnar jointing ("stone organs") of the Šomoška/Somoskő castle hill. Photo: P. Uher.

**Fig. 17.3.** Pentagonal and hexagonal jointing of the alkali basalt, Šomoška/Somoskő castle hill. Photo: P. Uher.

The basalts of the Cerová Formation can be classified as alkali olivine basalt and nepheline basanite. They represent products of intra-plate post-orogenic or anorogenic volcanism, possibly related to uplift of asthenosphere and formation of deep lineaments and faults in extensional/transtensional tectonic regime after Palaeogene to Miocene subduction and huge calc-alkaline andesite volcanic activity in the Western Carpathians. The age of the basaltic volcanic activity is constrained by K-Ar dating and biostratigraphy as Pliocene to Pleistocene, ~5 to 1 Ma, the Šomoška/Somoskő castle hill gave radiometric age of 4.08 ± 0.03 Ma (Vass *et al.*, 2000).

**Minerals of the basalt:** alkali basalt and nepheline basanite of the Cerová Basaltic Formation are masive rocks with olivine, pyroxene, amphibole, plagioclase, nepheline, rhönite and magnetite phenocrysts, as well as the same minerals and volcanic glass in the fine-crystalline groundmass (Konečný & Lexa, in Vass, 1992). Olivine forms tabular green crystals (usually up to 5 mm in size) and granular aggregates, locally up to several cm large. Their compositions show 77–85 mol% of forsterite and 15–23 mol% of fayalite (Mauritz, 1910 and Jugovics, 1913 – both in Koděra *et al.*, 1990). Pyroxene (Ti-rich augite with ~3.5 wt% $TiO_2$) and amphibole (kaersutite) forms black crystals up to 1 cm, crystals of titanian magnetite (~6.5 wt% $TiO_2$) are disseminated in the basaltic rocks (Koděra *et al.*, 1990). The vugs in the basaltic rocks are commonly filled by white zeolite incrustations.

Rarely, xenoliths of syenite and anorthoclasite composition occur in the alkali basalt of the Cerová Formation. These xenoliths probably represent lower crustal, partly metasomatized plutonic rocks. Rare finding of syenite xenolith with deep blue sapphire crystals (2 to 4 mm in size) in association with albite, anorthoclase, diopside (47–51 mol% $CaSi_2O_6$, 34–43 vol% enstatite and 9–19 mol% ferrosilite), leucite, contact metamorphic fibrolitic sillimanite and secondary analcime were described from alkali basalts/basanites of the Cerová Formation in the vicinity of the Šomoška/Somoskő (Uher *et al.*, 2006, Fig. 17.4). Consequently, such syenitic or anorthoclasitic xenoliths are the most probably parental rocks of pale to deep blue and pale violet crystals of sapphire, locally gem quality (1 to 9 mm large), found as isolated grains in the sedimentary filling of the Hajnáčka maar (Uher *et al.*, 1999, Fig. 17.5). The $\delta^{18}O$ isotope value of sapphire (3.8 to 5.85‰; Giuliani, written comm.) also indicate their magmatic, lower crustal to upper mantle origin.

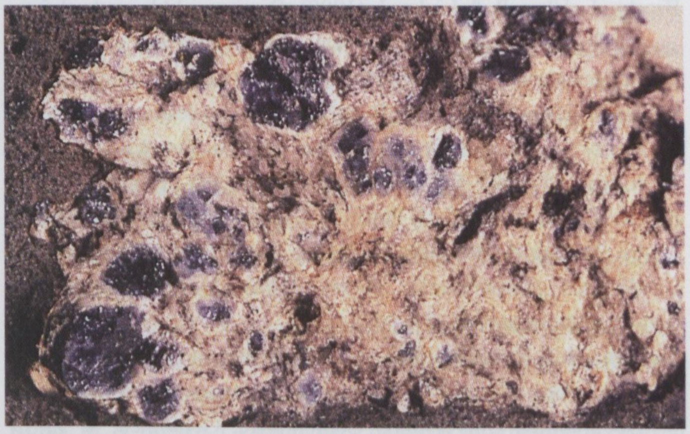

**Fig. 17.4.** Deep blue sapphire crystals (2 to 4 mm in size) in syenite xenolith, in alkali basalt. Gortva near Šomoška/Somoskő. Photo: S. Szakáll.

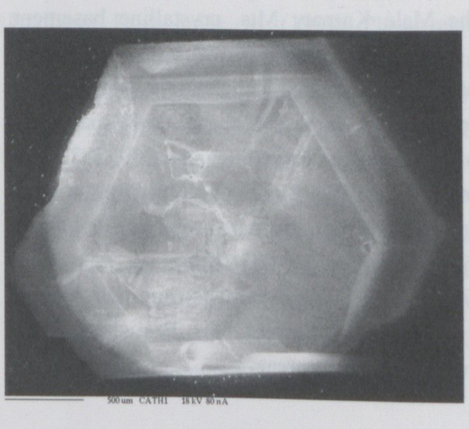

**Fig. 17.5.** Fine oscillatory zoning of sapphire crystal, Hajnáčka maar filling near Šomoška/Somoskő. Photo: D. Ozdín.

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## Appendix – Itinerary for IMA2010 SK1 field trip

### Monday, August 16, 2010 (Day 1)

| | |
|---|---|
| 09:00–10:30 | Bratislava downtown, Vajanského nábrežie 2 (N 48°08.41´, E 17°06.61´) The Natural History Museum, mineral coll. |
| 11:00–12:00 | Field stop 1: Bratislava, Rössler quarry (N 48°10.88´, E 17°07.11´) Granites and pegmatites |
| 12:30–13:30 | Pezinok town: Lunch |
| 14:00–15:00 | Field stop 2: Pezinok, Rybníček mine (N 48°21.57´, E 17°13.94´) Pyrrhotite-pyrite and V-Cr mineralization |
| 16:00–16:30 | Field stop 3: Modra, Harmónia (N 48°21.76´, E 17°18.54´) Granites, contact metapsammites |
| 17:00–18:00 | Field stop 4: Dubová, wineyards (N 48°22.03´, E 17°19.43´) Ca-skarn, leucogranites |
| 18:30 | Trnava: Dinner, wine tasting, accommodation |

### Tuesday, August 17, 2010 (Day 2)

| | |
|---|---|
| 10:00–11:00 | Field stop 5: Bádice, quarry (N 48°24.03´, E 18°08.17´) Phosphates-sulphates in metaquartzites |
| 12:30–14:00 | Banská Bystrica town: Lunch |
| 14:30–16:00 | Field stop 6: Ľubietová, Podlipa mine (N 48°44.78´, E 19°23.03´) Libethenite and other Cu-minerals |
| 17:00–18:00 | Field stop 7: Špania Dolina (N 48°48.46´, E 19°07.98´) Cu sulphide and secondary minerals |
| 18:30 | Špania Dolina village: Dinner, accommodation |

## Wednesday, August 18, 2010 (Day 3)

10:00–10:30 Field stop 8: Bešeňová (N 49°06.24′, E 19°11.22′) Travertine terraces
11:00–12:30 Field stop 9: Žiar Valley (Tatry National Park) (N 49°08.78′, E 19°42.11′) Banded amphibolites, metapelites
13:00–14:00 Liptovský Ján village: Lunch
15:00–18:00 Štrbské Pleso, Field stop 10: Starý Smokovec, Hrebienok (N 49°10.05′, E 20°13.10′) Granites, waterfalls, Tatry National Park
18:30 Tatranská Lomnica: Dinner, accommodation

## Thursday, August 19, 2010 (Day 4)

09:30–10:30 Field stop 11: Poprad, Kvetnica quarry (N 49°01.51′, E 20°16.90′) Mineralization in basalts-andesites
11:30–13:00 Field stop 12: Dobšiná, Ice Cave (N 48°52.11′, E 20°18.10′) Ice cave, Slovak Paradise National Park
13:00–14:00 Dobšiná (near the cave): Lunch
14:30–15:30 Field stop 13: Dobšiná, quarry (N 48°49.43′, E 20°21.98′) Serpentinite, chrysotile
16:30–17:30 Field stop 14: Gemerská Poloma, Dlhá dolina valley (N 48°46.11′, E 20°31.91′) Cassiterite, Nb-Ta-W minerals, greisens
18:30 Betliar castle: Dinner, accommodation

## Friday, August 20, 2010 (Day 5)

09:00–10:00 Field stop 15: Betliar (N 48°43.70′, E 20°31.95′) Tourmaline granite
11:00–12:00 Field stop 16: Ochtiná, Hrádok hill (N 48°39.89′, E 20°18.64′) Ochtiná aragonite cave
12:30–13:30 Fiľakovo town: Lunch
14:30–15:00 Field stop 17: Šomoška/Somoskő, castle hill (N 48°10.43′, E 19°51.65′) Alkali basalt, columnar basaltic jointing
17:00 Budapest, arrival